EUROPEAN COMMISSION

HORIZON 2020 PROGRAMME - TOPIC H2020-LC-BAT-2020

Solutions for large batteries for waterborne transport

GRANT AGREEMENT No. 963560

D1.4 – Battery circular economy in Europe

Report details

Deliverable No.	SEABAT D1.4	
Deliverable Title	Battery circular economy in Europe - Impact on battery production in EU and its circular economy	
Deliverable Date	2021-06-28	
Dissemination level	Public (PU)	
Author	Driss Madouch (FC-SI)	2021-06-28
WP leader	Andrea Lombardi (FC-SI)	2021-06-28
Reviewers	Alfonso Carneros (SOERMAR) Peter Rampen (DAMEN) Cor van der Zweep (UNR)	2021-06-23 2021-06-23 2021-06-30
Coordinator	Jeroen Stuyts (Flanders Make)	2021-06-23

Document History

Version	Date	Author	Remarks
V0.1	2021-06-09	Driss Madouch	For Technical Review
V0.2	2021-06-18	Driss Madouch	For Quality Review
V0.3	2021-06-28	Driss Madouch	Final emission
V1.0 Final	2021.06.30	Cor van der Zweep	Final version for submission

Project Abstract

The goal of the SEABAT project is to develop a full-electric maritime hybrid battery concept that is based on:

- Modularly combining high-energy batteries and high-power batteries,
- novel converter concepts and
- production technology solutions derived from the automotive sector.

The modular approach will reduce component costs (battery cells, convertors) so that unique ship designs can profit from economies of scale by using standardised low-cost components. The concept will be suitable for ships requiring up to 1 MWh of storage or more.

Project Abstract

The goal of the SEABAT project is to develop a full-electric maritime hybrid battery concept that is based on:

- Modularly combining high-energy batteries and high-power batteries,
- novel converter concepts and
- production technology solutions derived from the automotive sector.

The modular approach will reduce component costs (battery cells, convertors) so that unique ship designs can profit from economies of scale by using standardised low-cost components. The concept will be suitable for ships requiring up to 1 MWh of storage or more.

Public summary

As already highlighted in the other deliverables of this project, battery systems are a fundamental and strategic technology for the decarbonisation of transport systems and, in general, for the energy systems of the future. Therefore, the EU has identified batteries as one of the most important and strategic technologies to invest in, with the aim of developing a European industrial chain that can compete with those world leaders in this area.

In this context, Europe is currently the centre of gravity of this technological change from the users' point of view. From the point of view of manufacturers, however, lithium-ion technology has a centre of gravity on Asian countries, which hold ownership of the main raw materials necessary for the development of battery cells.

To partially remedy this condition, Europe will have to develop policies and strategies that will allow it to find the raw materials necessary to develop its own industrial chain of battery systems through the recovery and recycling of the current generation of batteries.

To this end, this document proposes:

- The analysis of the main suppliers of the materials necessary for the development of the battery systems (from the cells to the module),
- the process flow required for system development by battery manufacturers, highlighting costs, times and associated energy consumption,
- the main steps required for the integration of these systems safely on board the ship,
- the possible recycling policies of disused systems in order to reduce the environmental impact of batteries and, at the same time, increase European independence from Asian countries for the raw materials necessary for the development of these systems,
- the identification and development of policies for the so-called "second life" of batteries, in order to extend their operational life and reduce the costs of systems for applications that are not demanding from the point of view of dimensions (such as services to the European electricity network or 'coupling with the renewable generation to reduce its randomness),
- the development of a preliminary LCA, based on two significant case studies and evaluating different operating conditions and different end-of-life policies.

Contents

1 Introduction

A circular economy for batteries is an economically viable battery value loop which aims to optimize the value of the raw materials, negate the environmental impact of batteries, and does not push externalities onto those less able to deal with them. In other words, there is no option to dump batteries in a landfill which pollutes the environment and locks away valuable materials.

In a truly circular future system, batteries would be redesigned for remanufacture or reuse, are collected and at end-of-life all materials are recovered and, as their material value is optimized (i.e. they are not down cycled), are reused in other batteries or products.

Instead of end-of-life landfill, recovery of end of-use batteries for refurbishment or reuse is the key for the transition to a circular economy, as shown in Figure 1. Materials selected for batteries would be able to be separated into benign biological materials (and used to regenerate nature) and technical materials which would be reused.

Materials would be recovered at their highest value - i.e. with their 'value optimized' - at end of life. Of course, the circular economy is not just about material flows [1].

Lithium-ion batteries are currently designed and sold in ways that mean they are difficult to repair, remanufacture, and recycle. These are "traditionally welded or glued together, making individual components difficult to replace. If one part fails, the whole battery is usually thrown away — often with more than 80% of its potential life left unused."

Two important issues are raised here: first, batteries with most of their charging capacity remaining are being discarded rather than used; and second, the valuable materials that are used to make these batteries are being lost from the economy. With a shortage of lithium possible as soon as 2025, this could be a major barrier to the uptake of renewable energy and zero emission transport.

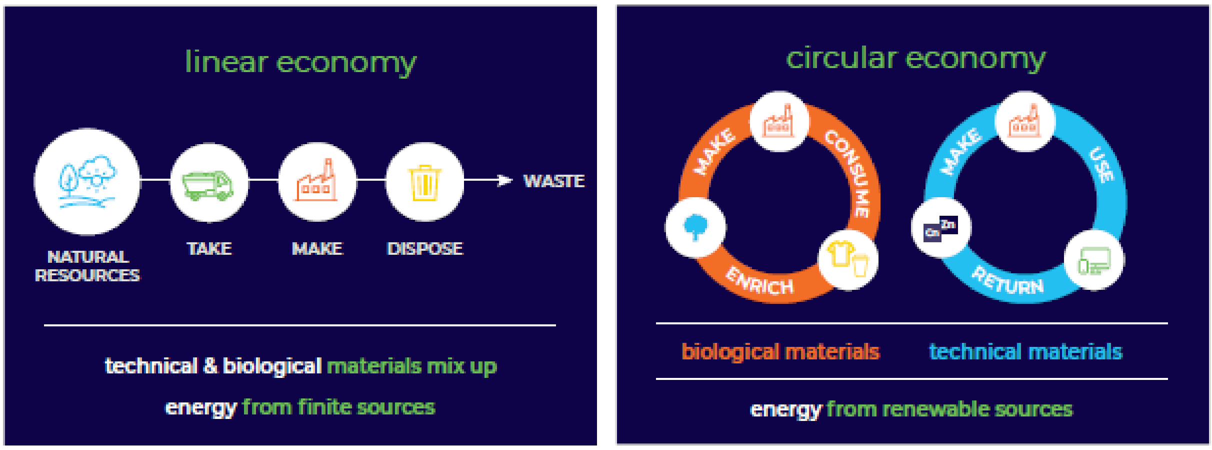


Figure 1 - From linear to circular economy.

1.1 Purpose of the document

The main objective of the document is to provide a detailed analysis of the different impacts of battery systems for marine use on the European circular economy. To this end, analyses are presented related to:

- availability and impacts of the raw materials needed to build batteries,
- identification of possible risk in the European supply chain,

- the energy needed for battery development,
- requirements, constrains and tests required for the on-board integration of batteries,
- recycling strategies and policies and their impact on the European circular economy,
- Life Cycle Assessment of batteries used for two maritime case studies.

1.2 Document structure

This document has been divided as follows. **Chapter 2** provides a brief description of the methodology agreed and applied between the Work package partners to divide the research work, identify the bibliographic material, organize specific meetings for each research area, collect the contributions of the partners, review the contributions and integrate them into the this document.

Chapter 3 presents the main results of the activity. In particular, the chapter will present:

- An analysis of lithium-ion batteries material providers and investment plans;
- An analysis of battery manufacturing process, also considering the cost, time, and energy consumption required;
- A list of steps, skills and requirements for the on-board integration of battery systems;
- An analysis of current recycling strategies and policies for batteries;
- A Life Cycle Analysis (LCA) for two case studies, considering the possible integration of battery systems for different purposes.

Finally, **Chapter 4** draws some conclusions and proposes recommendations for the next Work Packages of the project.

2 Methods

The methodology identified, agreed and applied for the development of this activity and of this document envisaged the implementation of several phases, the main ones being:

1. Organization of specific meetings and committees (steering and technical committee) for the different tasks of the project's WP1, to identify the main technical activities and follow their development.

2. Identification of the skills of the partners involved and consequent assignment of contributions and activities based on the same skills.

3. Development by the task leader, in agreement with the partners, of the preliminary index of the document and assignment to the partners of the areas to be developed.

4. Identification of possible sources of technical, environmental and bibliographic information, with relative sharing between the partners of the information and selected databases.

5. Development of the technical contributions by the partners in charge for each point to be developed in the document.

6. Preliminary review of contributions by the task leader and update of contributions.

7. Collection of technical contributions and their integration within the deliverable D1.4.

8. Review of the preliminary document by the partners and subsequent updating of the document by the task leader in function of the information received.

9. Final emission of the document D1.4 by the task leader.

2.1 Partners involved and contributions

The partners involved in the development of this document are:

- **Fincantieri SI**, as WP and Task leader, contributor for the battery integration on-board, circular economy and LCA;

- **ABEE**, as contributor for material providers analysis, battery manufacturing and recycling.

3 Results

3.1 Material providers

3.1.1 Material Provider Introduction

Lithium-ion technology development and manufacturing is driven by consumer electronics (e.g. portable electronic power). A rapidly growing market is destined for battery electric vehicles (BEV). At the end of their life batteries can be either recycled or used in a second applications. Considering the value chain for batteries, the battery and material providers could be divided into the following six categories.

Categories	Description
Raw material mining	The elements used in Li-Ion Battery cells are harvested from raw materials. These are mined from the earth's crust or recovered from Water. [1] Following elements are, inter alia, used in Li-Ion Battery cells: Lithium (Li), Nickel (Ni), cobalt (Co) aluminium (Al), manganese (Mn), copper (Cu), silicon (Si), titanium (Ti), carbon (C),…
Cell component manufacturing	Production of different cell components (Anode, Cathode, Electrolyte & Separator)
Cell manufacturing	Assembly of the different components into an individual cell
Battery System manufacturing	The produced Li-Ion cells are then assembled for use in portable electronic devices or battery packs
Original Equipment Manufacturer (OEM)	e.g., Electric Vehicle Manufacturing or cell phone manufacturer
Battery Recycling	Re-use or second use of batteries and materials.

Since the activity of the major global and EU players often cover different segments of the value chain, it is difficult to consider the main players of each segment independently. This report focuses mainly on the raw materials and cell components and will outlines the major players in Europe.

3.1.2 Overview of the material providers

Europe reliance on other countries along the whole Li-Ion cell supply chain goes beyond the raw and processed materials. The Figure below (Figure 2) shows the key players from raw materials to Li-Ion cells manufacturing by country and their market share in percent. The raw materials, processed materials and components that have been considered in the study are also indicated. The figure has been created based on the 2019´s JRC report "Materials dependencies for dual-use technologies relevant to Europe's defence sector". [2]

Considering the fact that the data used is few years old and the Li-ion battery industry is currently undergoing a period of transition, the actual figures may vary.

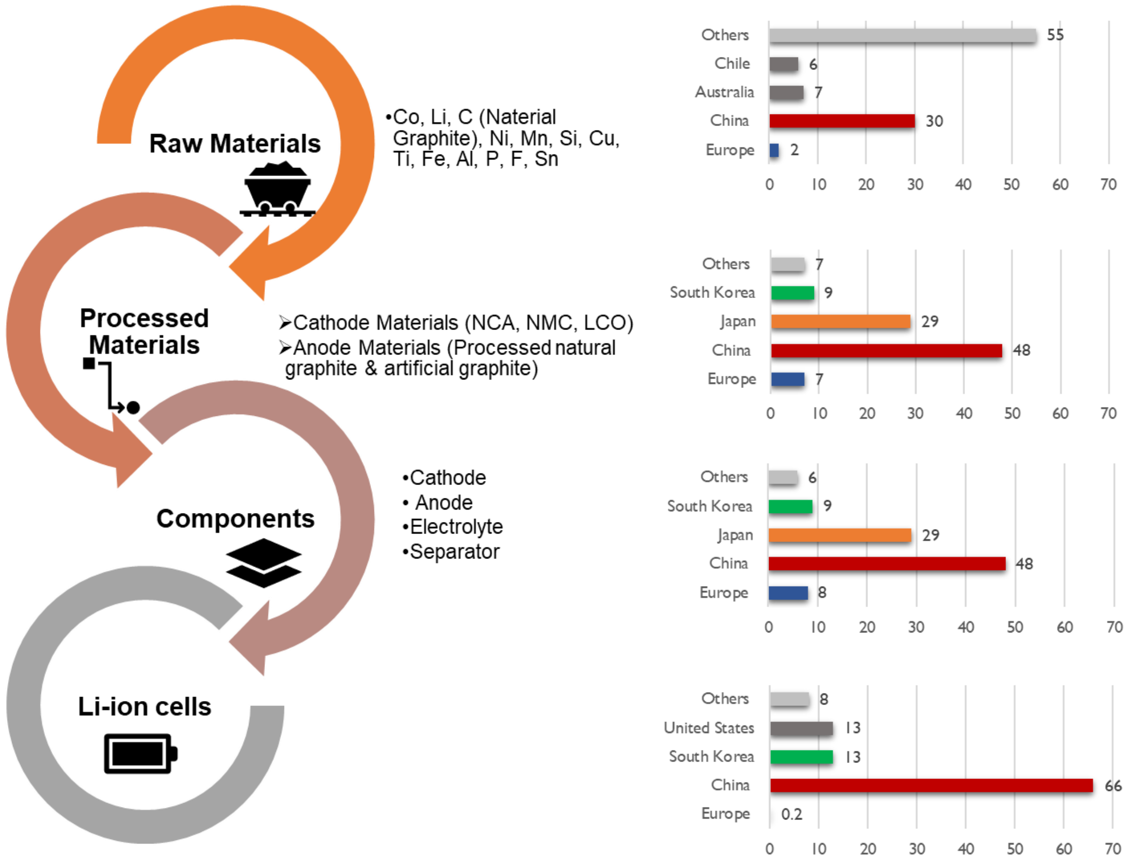


Figure 2: Key players in the Li-Ion supply chain and market shares in percent

Europe's dependency on Asia is evident. China is the major supplier throughout the whole supply chain. South Korea and Japan are key players for processed materials and components. Almost 92% of the Li-ion cells are manufactured in China, South Korea and the United States. Europe produces 2% of raw materials and manufactures less than 1% of battery cells. Due to the very dynamic development in the last years, Europe`s shares might be higher.

3.1.3 Risk in supply chain for Europe

An overview of supply risk in Europe in the supply chain of Li-ion cells is shown below (Figure 3). High risks are detected for the assembly and the supply of raw materials. This exposes the Li-ion industry in Europe to supply uncertainties.

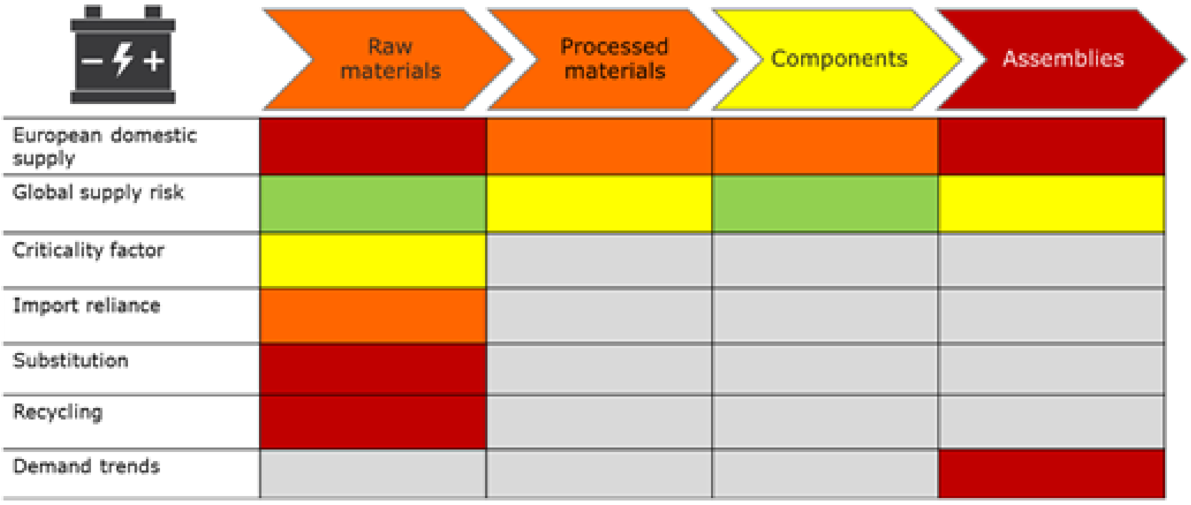


Figure 3: Supply risk and bottlenecks in the supply chain of Li-ion cells/Batteries [2]

3.1.4 Material providers by segment & cathode manufacturing in Europe

In the following the situation of the material providers both worldwide and at European level is showed. The situation is highlighted for raw materials, processed materials, cell components and Li-Ion cells. The dependency of Europe on Asia in that respect is underlined.

3.1.4.1 Mining and processing

The figures have been created based on data from the Joint Research Center (JRC) report "*Raw materials in the battery value chain" published in 2020* [3]. The report emphasizes, inter alia, the current supply situation of important raw materials. Cobalt, natural graphite and silicon metal are considered as critical for Li-Ion batteries.

Figure 4 shows in percent the global mine production output shares for Cobalt, Lithium, and natural Graphite. [3] Cobalt mining & production depends heavily on two countries. Around 54% of the global cobalt mining originates from the DRC (Democratic republic of Congo). A large part of refined Cobalt (46 %) comes from China. (Status 2016)

Most of the lithium mine originates from Chile, Australia, and Argentina. 45% of the world's lithium hard-rock minerals refining capacities are in China. Chile and Argentina produce more than 50% of the refined lithium from brine operations.

While China is responsible of around 70% of the global production of natural graphite, only 10% is intended for the battery anode material manufacturing. With an increasing demand, a more expensive synthetic graphite can substitute the natural graphite in the future. Two thirds of the Nickel's supply depend mainly on Indonesia, Philippines, Australia, Russia and Canada. 30% of the refined Nickel comes from China.

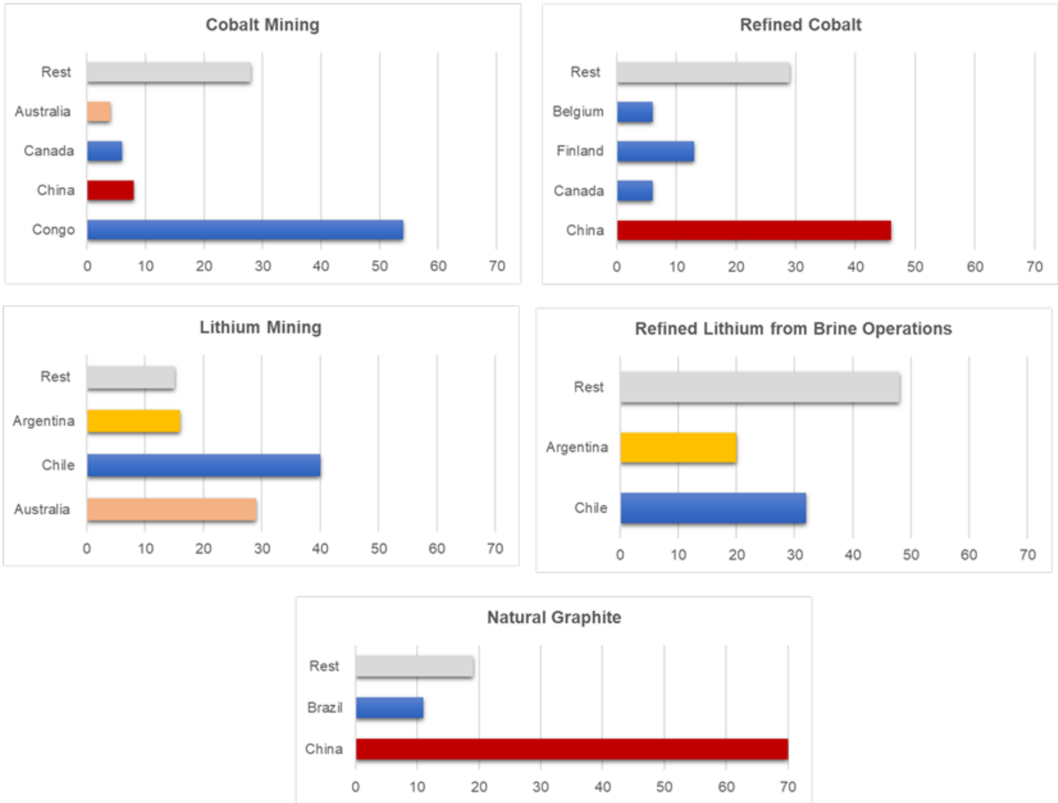


Figure 4: Global mine production output share for Cobalt, Lithium and Natural Graphite

3.1.4.2 Processed materials and Li-ion cell components

A closer look at the processed materials shows again in detail the Asian dominance on the market. (see Figure 5). 86% of the processed materials relevant to Li-ion batteries originates from China, Japan and South Korea. Europe is dependent on the supply of graphite (natural & artificial), NCA cathode material, anode and separators [2]. Even the produced NMC and LCO cathode materials might not be enough the meet the European demand in the future.

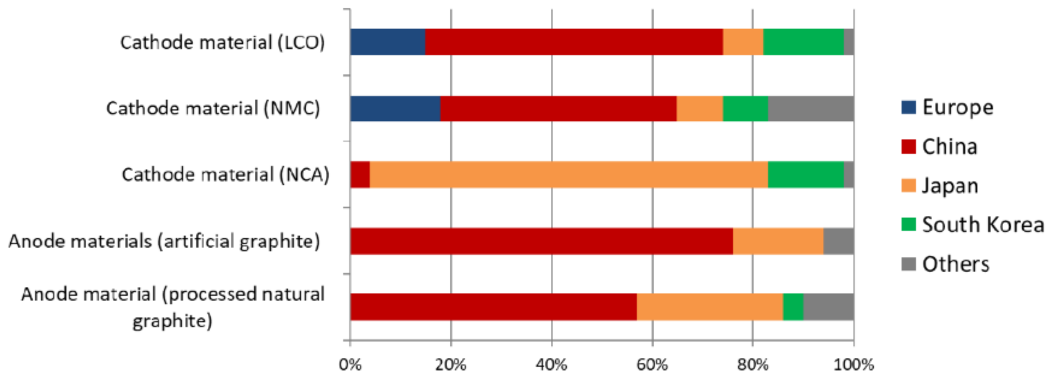


Figure 5: Country production shares of processed materials relevant to Li-ion batteries [2]

Similar to processed materials, the three Asian countries (China, South Korea and Japan) dominates the supply of Li-ion cell components [Fig. 5]. 30% of cathode materials are produced by European companies. 4% of electrolytes originates from Europe. [2]

Some anode manufacturers are emerging in Europe such as E-magy and Nanomakers for Silicon anode and Talga group for graphite in Sweden. For Carbon additives there are Imerys in Belgium and Cabot corporation in Netherlands.

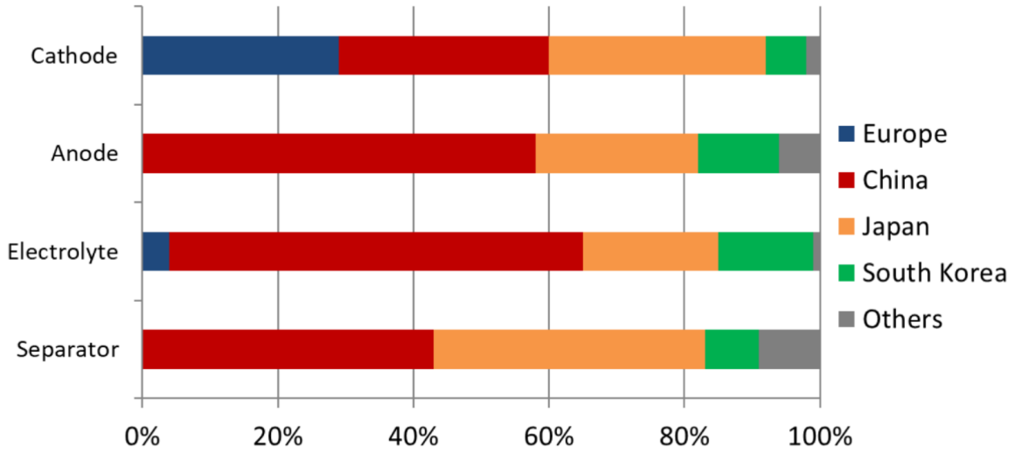


Figure 6:Country production shares of components relevant to Li-ion batteries [2]

3.1.4.3 *Cathode Manufacturing in Europe*

The choice of the cathode type defines the cost of the battery cell and influences the need for different active materials like Cobalt, Nickel or Manganese. Cathode manufacturing plays an important role in the battery supply chain.

Over the next two decades Europe cathode demand is expected to increase significantly. The development of the cathode manufacturing is closely related to the electric vehicles sales and the investment in Gigafactory's. As shown in Figure 7, the difference between cathode demand and production highlights that the European cell manufacturers will rely on foreign sourced cathode supply. The forecast is based on a market study performed in 2020 by Roskill [4], a leader in critical material supply chain consulting. The study includes cathode production targeting Lithium-ion EV batteries. In the long-term Europe's cathode production is expected to stagnate at 200 kt.

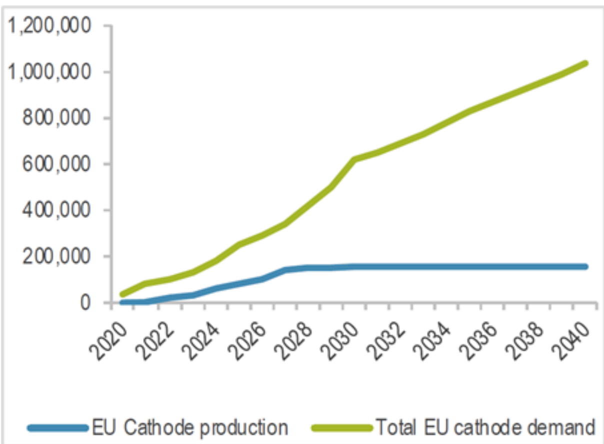


Figure 7: Forecast of EU cathode demand vs Production in Tons [4]

The four main key players targeting the production of cathode active material in the EU are shown below. Only Northvolt intends to provide its cell cathode requirement 100% internally. It is expected that the EU will focus on high-nickel cathode chemistries like high-nickel NMC and eLNO. [4]

Figure 8 highlights the market share of the different companies. In 2020 Umicore has a market share of 100%. In the coming years, the new market players will reach commercial scale production of cathode materials. By 2030 Umicore will keep its leading position, totalling around 33%. Depending on the growth of the European EV market and the cell manufacturing capacity, additional investments in cathode production capacity, likely from Asian cell makers, will be planed.

Company		Description	Plan location & Forecast chemistry production
umicore	Umicore	Materials technology company from Belgium	Plant location: Nysa, Poland NMC 622, NMC 712, NMC 811 Deliveries started in late 2020 [5] [6]
BASF We create chemistry	BASF	A German multinational chemical company. The largest chemical producer in the world.	Plant location: Schwarzheide, Germany NMC 622, NMC 712
JM	Johnson Matthey	A British company specialized in chemicals and sustainable technologies	Plant location: Poland eLNO 3% Co Expects to start production in 2021-22 of battery materials with improved performance and reduced cobalt content. [5] [6]
northvolt	Northvolt	Swedish battery developer and manufacturer, specialized in lithium-ion technology for electric vehicles.	Plant Location: Skelleftea, Sweden NCM 622, NCM 712, NCM 811 Plans to build its cathode in-house.

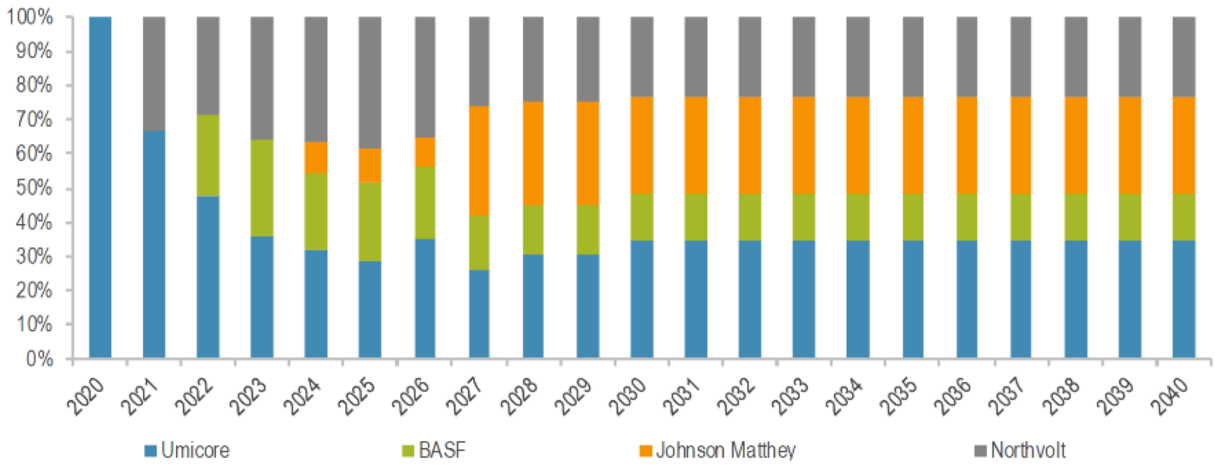
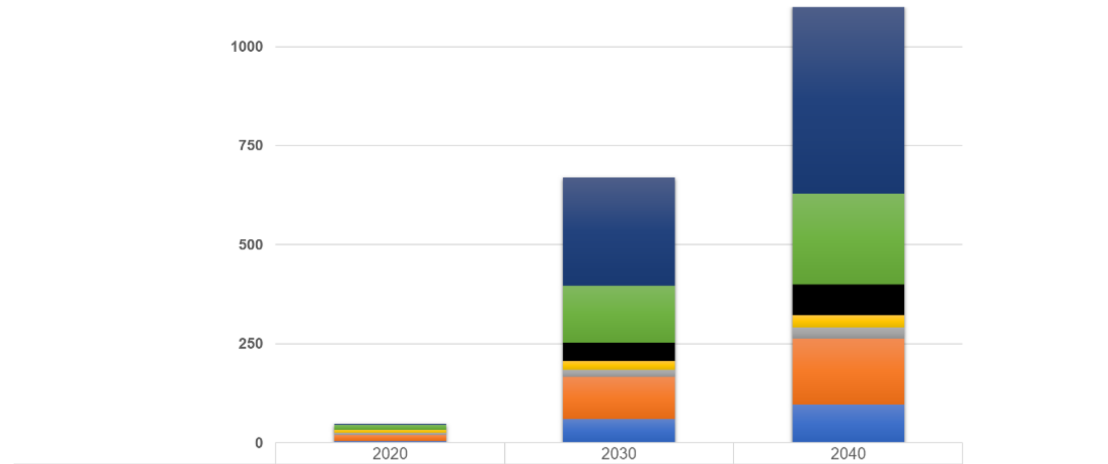


Figure 8: European cathode producer market share between 2020 and 2040 [4]

3.1.5 Li-Ion cells and investment plans

In the last years major efforts have been made to increase the production of Li-Ion cells in Europe. In the next two decades, the European battery capacity will be further expended. This is mainly due to large investment in Gigafactory's. The expected European capacity in the next two decades is shown below. Tier 2 suppliers like Northvolt, SVOLT and Farasis are not showed in detail. The predictions have been conducted by Roskill [4] based on the sales data and the plan announcement of large automakers. The production capacity in Europe is expected to grow from 47 GWh in 2020 to 670 GWh by 2030. The consulting company Roskill anticipates a total of 1104 GWh by 2040.



	2020	2030	2040
Tier 3	3	274	475
Tier 2 (Farasis, Northvolt, Svolt,...)	12	144	230
Tesla	0	46	76
SKI Innovation	8	21	31
Samsung SDI	5	19	29
LG Chem	15	107	166
CATL	5	59	97

Figure 9: European battery capacity by companies in GWh

The main investments originate from CATL, LG Chem, Northvolt, Svolt. Some Tier 3 suppliers like Britishvolt, PSA-SAFT Consortium, Morrow Batteries and FREYR announced large investments in Gigafactory`s. [4] The map below shows different investments in the future years. (Figure 10)

Verkor, a French industrial company, is having plans to make indigenous battery technology with reduced import of materials. The production of the first Gigafactory is scheduled to begin in 2023, with a capacity of 16 GWh. [7]

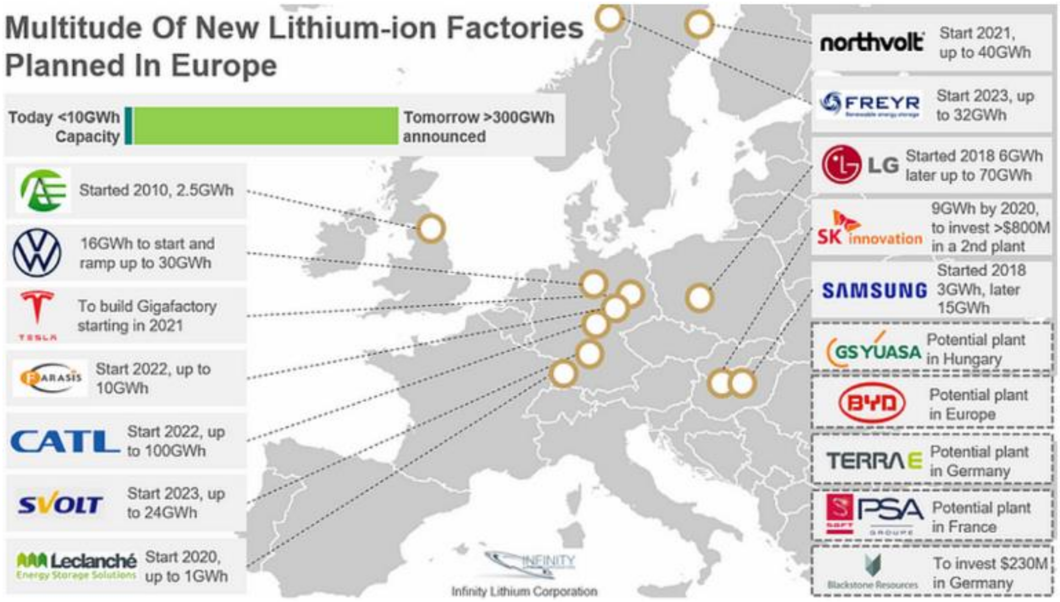


Figure 10: Planned Lithium-ion factories in Europe [6]

Different European players are targeting to close the loop and to establish themselves on the market in the long term. Still, most investments are from Asia. Following is a list of companies, that are planning an increased expansion in the European market. Most of the initiatives are motivated by the growing market of the Electric Vehicles.

Company		Description	Plan
	CATL	Contemporary Amperex Technology Co Chinese Battery cell manufacturer	Gigafactory in Germany (Erfurt) 14 GWh by 2021 (100 GWh by 2025) Based on the increase in demand, CATL is planning a 100 GWh by 2025. Among the customers: BMW, Daimler, PSA Group. Volvo and Jaguar [8] [9]
	LG Chem	Largest Korean chemical company	Expansion from 4 GWh to approximately 12 GWh by April 2021. Goal is to power roughly 300.000 EVs. LG Chem has an agreement to supply VW with battery cells for the ID.3 models. [10]
	NorthVolt	Swedish battery developer and manufacturer, specialized in lithium-ion technology for electric vehicles.	32 GWh by 2023 in Sweden. This enters in the context of the EU to create local battery suppliers to compete with the established Asian players like CATL and LG Chem. [10]
	SK Innovation	South Korea based battery manufacturer	Existing capacity: 7.5 GWh. SK Innovation Plans a new plant with an additional capacity of 7.5 GWh in Hungary. Start of mass production by 2022 once product certification is complete. [10]
	Samsung	South Korean multinational company.	Completed a plant in Hungary during 2018 capable of supplying battery packs for 3 GWh [[10]
	Farasis	Chinese Li-ion battery technology company fosued on developing energy storage	Plan to invest 600M Euros to build a plant in Germany capable of producing 6 GWh. The plan capacity will be later extended to 10 GWh. The plant will produce cells, modules and potentially packs starting from 2022 [10]
	Volkswagen	German Car & Trucks manufacturer	VW recently announced to partner with NorthVolt to build battery cells in Salzgitter (Germany) The initial capacity will be 12 GWh with potential growth up to 30 GWh over time. VW's interim target is to produce 3 Million EVs per year by 2025, assuming an average battery size of 60 kWh, the plant would cover 20% of the company's needs. [10] VW announced in March 2021 plans to reduce battery costs by up to 50 percent and to build Six Gigafactory's with a total production capacity of 240 GWh in partnership model. [11]

Given by the risk in producing the battery cells due to its unforeseen material supply-demand and complicated cell chemistry, most of the EV car manufacturers are not taking the action to produce the batteries by themselves. For example, VW has announced plans to partner with Northvolt to build a battery cell plant in Salzgitter, Germany**.**

ACC (Automotive Cells Company), a joint venture between the Group PSA/Opel and Total, started the development of new high-performance lithium-ion technologies. Two “Gigafactories” with an initial capacity of 8 GWh (reaching a cumulative capacity of 48 GWH) could be launched in France and Germany. [12]

Since the Lithium-ion technology development is primarily driven by consumer electronics and automotive market, materials and battery providers have not developed strategy related to the maritime industry. The current projects in the maritime industry focus on evaluating the available technology and how to integrate it into a maritime environment [13].

3.2 Battery cells manufacturing

3.2.1 Summary

This part focuses on the current situation of the battery manufacturing process, cost analysis, and energy consumption. First, we go through the subject in terms of the entire process, in the three mentioned main parts, then research the issues and analyze the concept for the common parts.

3.2.2 Introduction

Around 25% of the cost of the battery is due to manufacturing, but despite this there is no great progress in the process [14]. The production of the lithium-ion battery cell consists of three main process steps: electrode manufacturing, cell assembly, and cell finishing.

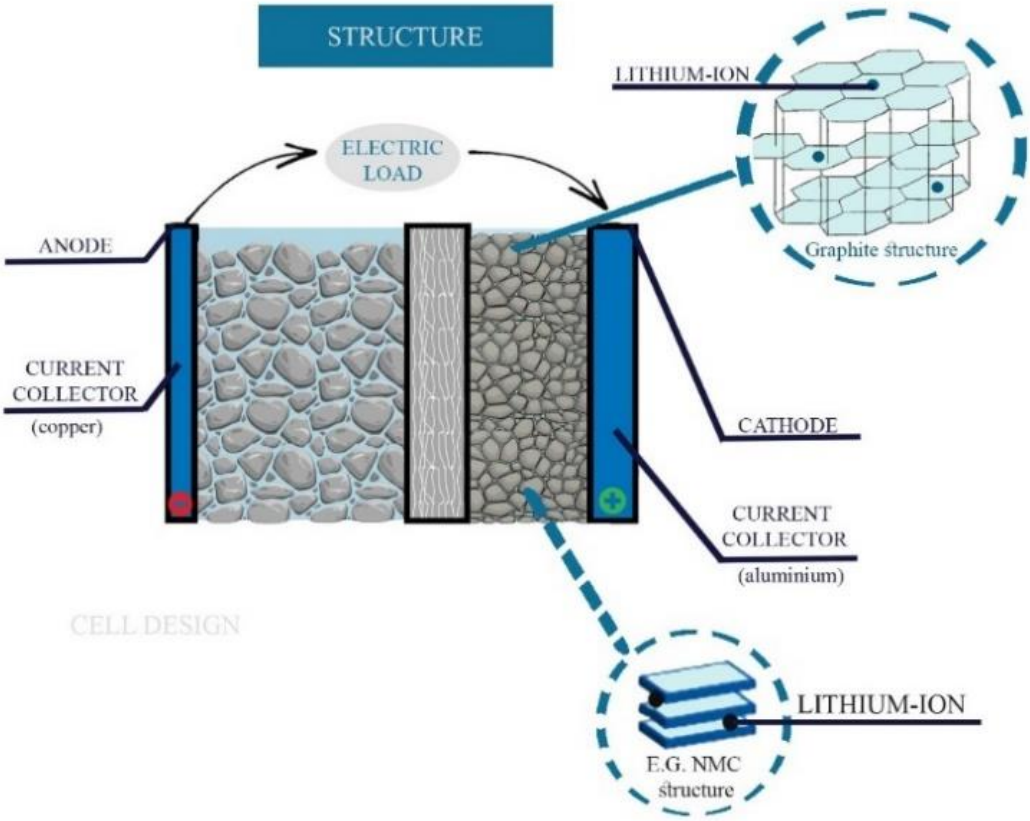


Figure 11: Main battery characteristics

To have a better understanding of cell characters, figure 1 shows a schematic view of a battery. Even though LIB manufacturers have different cell designs such as Pouch (LG Chem, A123 Systems, SK innovation), Prismatic (CATL and Samsung SDI), and cylindrical (Panasonic), the cell production process are similar together. The entire process can be shown in the following picture:

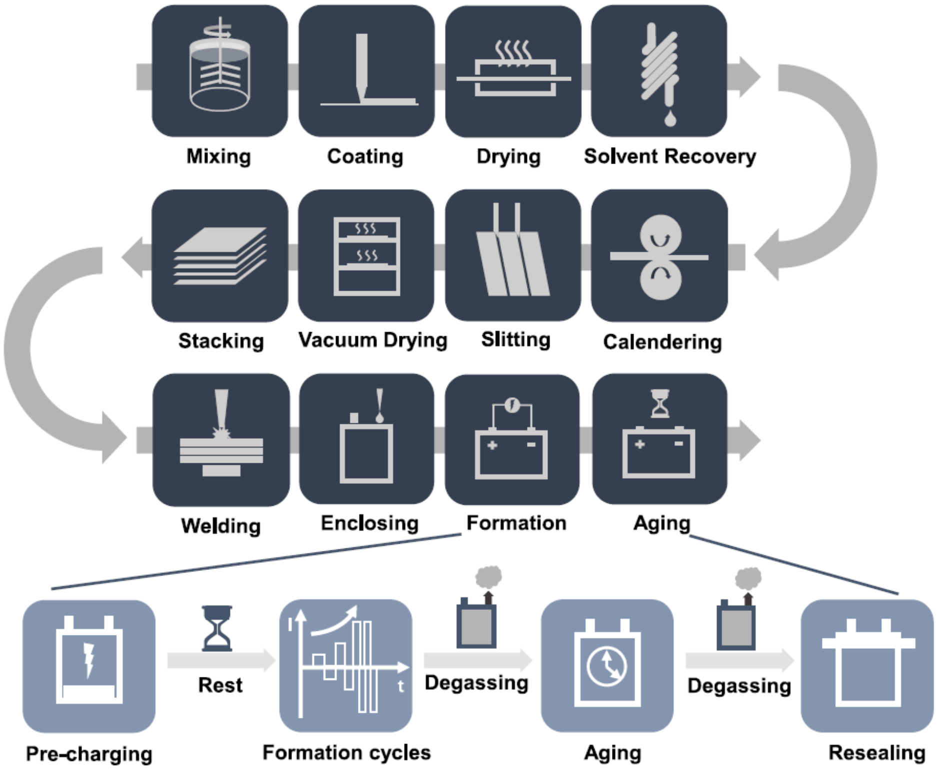


Figure 12: Current state of the art of battery manufacturing process [15]

3.2.3 The processes

3.2.3.1 Electrode manufacturing

The first step is that three elements which are the active material (AM), conductive additive, and binder mixed to create a homogenous slurry considering solvent. Regarding the cathode part, N-methyl pyrrolidone (NMP) is applied to dissolve the binder which is polyvinylidene fluoride (PVDF). In the anode part, the styrene-butadiene rubber (SBR) is dissolved with carboxymethyl cellulose (CMC). The created slurry is pumped into a slot die or doctor blade coated on the current collector which is an Aluminum foil for cathode and copper foil for the anode and they are transferred to drying equipment in terms of evaporating the solvent. Because NPM is toxic the solvent recovery process is mandatory for cathode production in the drying process and the recovered NMP can be reapplied 70 to 80 percent [16]. For the water-based anode slurry, the harmless vapor can be exhausted. Therefore, the calendaring process can be helpful to moderate the physical properties of electrodes. After this process, the electrodes are stamped and slitting to the related size of the cell. After that, to remove the excess water the electrodes are delivered to the vacuum oven. After drying the moisture level of electrodes is inspected to being sure about corrosion aspect and side reaction of the cell in which they should be minimized. After this part, the electrodes are delivered to the dry room with dried separators for producing cells.

3.2.3.2 Cell enclosing

The electrodes and separator are stacked or winded by layer to create the internal structure of the cell. The aluminum and the copper tabs are joined or welded to the cathode and anode current collector. The welding techniques are related to the cell type applied which are discussed in the welding part. Then, the cell stack is delivered to the designed enclosure which does follow an international standard and every manufacturer has its unique standard related to the purpose of the cells. Then the enclosure is filled with electrolyte before the final sealing and the cell production is completed.

3.2.3.3 Cell finishing

In this step, the electrochemistry activation steps are utilized for cells in terms of operational stability. An SEI layer can protect the unalterable electrolyte consumption during fast charging resulting in dendrites [17]. The formation and aging process initiate from charging and continues to rest session for electrolyte wetting. The charging rate in this level is C/20, and the rate is increased gradually to guarantee a stable SEI layer on the anode [18]. The formation process generates gas which should be discharged due to safety concerns. After or during the formation cycles, cells are placed in the aging racks to finish the electrolyte wetting and Solid Electrolyte Interphase (SEI) stabilization. The other degassing is applied before final sealing based on the related application. Based on the formation standards and aging temperature, this phase might take several weeks.

3.2.4 Cost, time, and energy consumption

To evaluate the battery manufacturing process, cost per year, throughput and energy consumption should be considered:

3.2.4.1 Cost estimation

To evaluate the cost and energy consumption, one way is to determine each step. The following diagrams show the cost breakdown structure of manufacturing cost evaluated by the BatPac model done by Argonne National Laboratory. The model considers a 67-Ah NMC622/graphite cell for one hundred thousand battery packs/year plant [19].

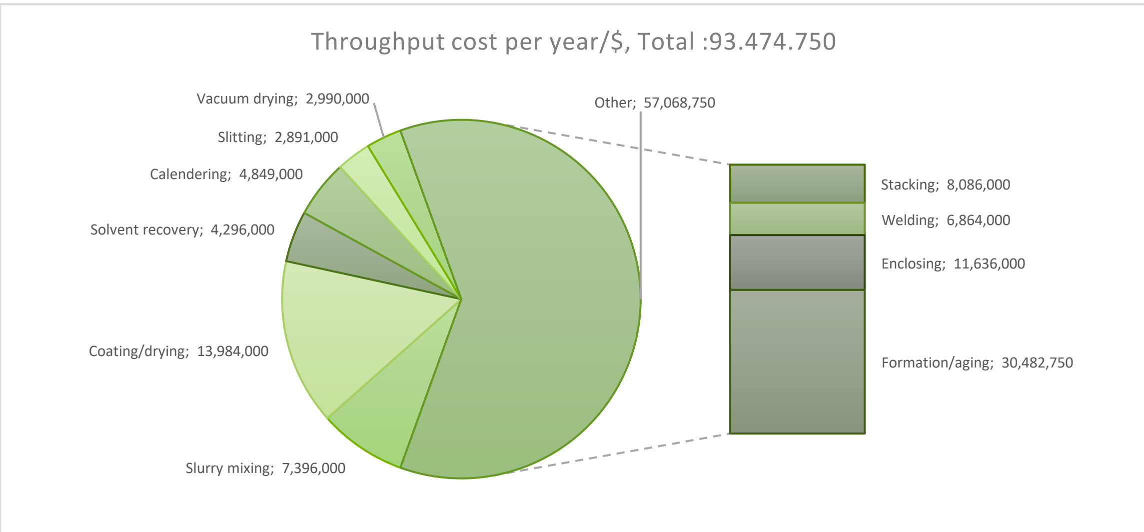


Figure 13: Battery manufacturing throughput cost per year

3.2.4.2 time estimation

Battery manufacturing cost is highly related to the time of production because it might affect the battery cost. The following table shows the information related to the battery throughput manufacturing process. The following table shows the related information.

Manufacturing process	Throughput
Slurry mixing	30 min–5 h
Coating/Drying	35–80 m/min
Solvent recovery	Depends on the techniques.
Calendaring	60–100 m/min
Slitting	80-–150 m/min
Vacuum drying	12–30 h
Stacking	Depends on the electrode dimension.
Welding	Depends on the techniques.
Enclosing	Depend on the cell design.
Formation/aging	Up to 1.5–3 weeks

Table 1: Time-consuming for a battery production [20]

Table 1 shows the critical part is formation and aging, which should be considered the most critical path in the diagram.

3.2.4.3 Energy consumption

As mentioned before, the process of all kinds of batteries in terms of the production processes are remarkably similar. In this part, research done by [21] is considered for a 32-Ah lithium manganese oxide (LMO)/graphite cell production was shown. The total energy consumption for this cell is 13.28 kWh/cell, that means a total energy consumption of 112 KWh of energy for each kwh of cells produced.

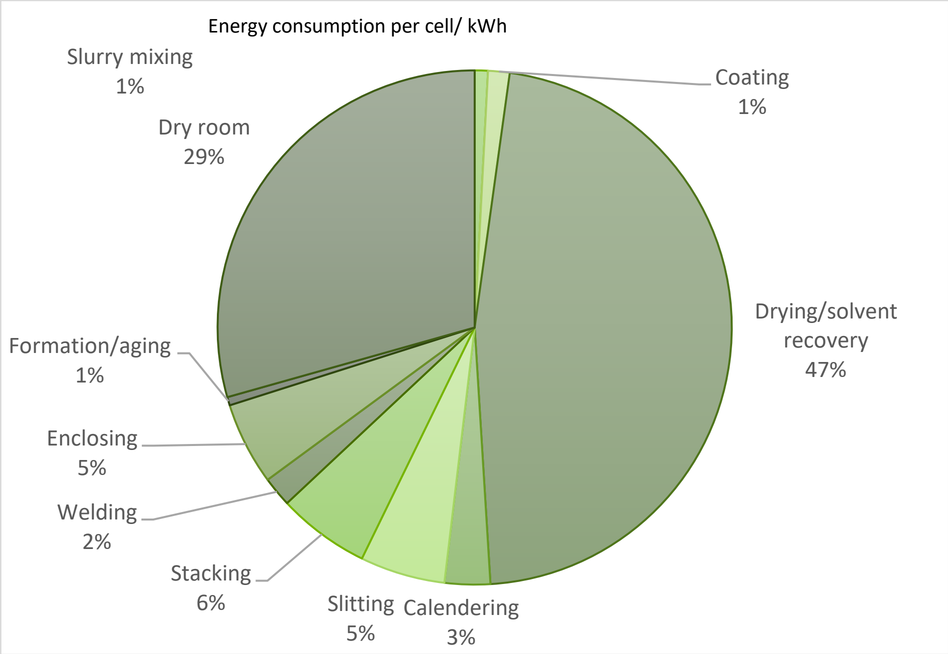


Figure 14 Energy consumption per cell/kWh

3.2.5 Subprocess and schematic illustrating of the manufacturing process

In this part, we go through some common battery parts and show the schematic views of some processes and the flow process.

3.2.5.1 Slurry mixing:

As Figure 15 shows mixing is an expensive step. Figure 15 shows the schematic view of slurry mixing and Figure 16 shows the process of slurry mixing.

Figure 15 schematic view of slurry mixing

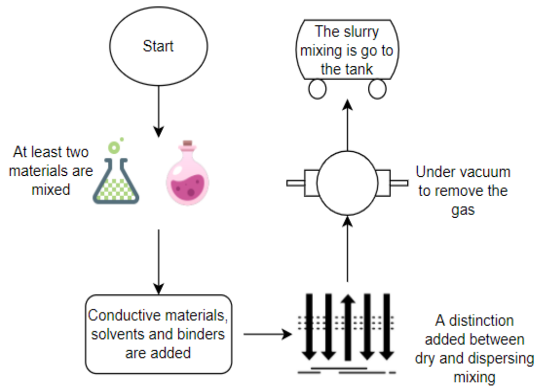


Figure 16 Processes of slurry mixing

3.2.5.2 Coating, drying, and solvent recovery:

This total process takes about one-fifth of the total manufacturing cost. Figure 17 shows the schematic view, Figure 18 shows the manufacturing process. To have a better investigation Figure 19 shows a schematic view of drying and the diagram process has been shown in Figure 20.

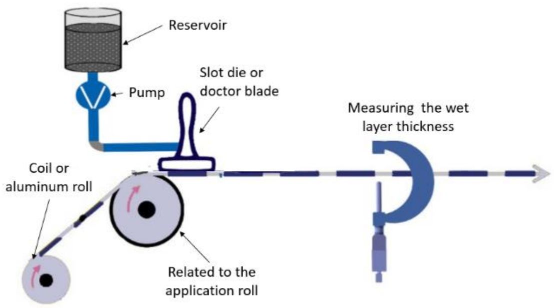


Figure 17 schematic view of the process of coating, drying, and recovery.

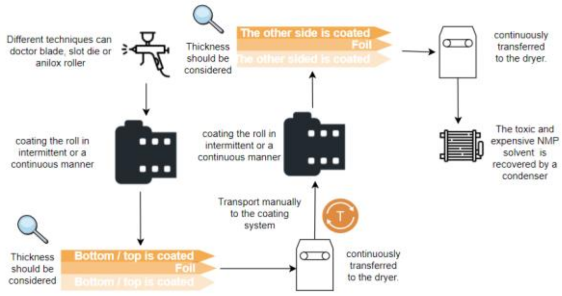


Figure 18 Process of coating, drying, and recovery.

3.2.5.3 Drying

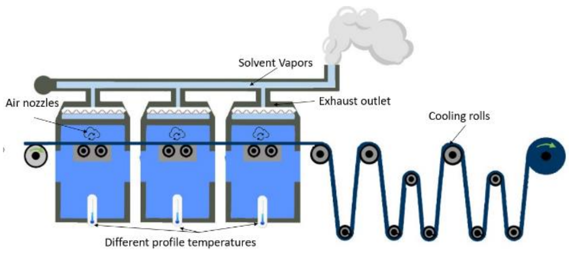


Figure 19: schematic view of the process of drying.

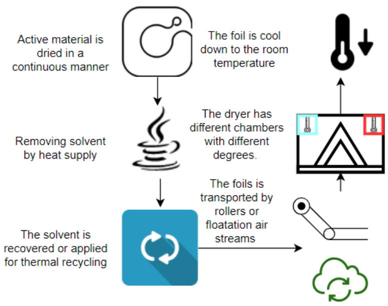


Figure 20 Process of Drying

3.2.5.4 Calendering

In this process, the aluminium and copper foils are coated on each side. Then, they are compressed by rotating a pair of rollers. Figure 21 and Figure 22 show the process of calendaring.

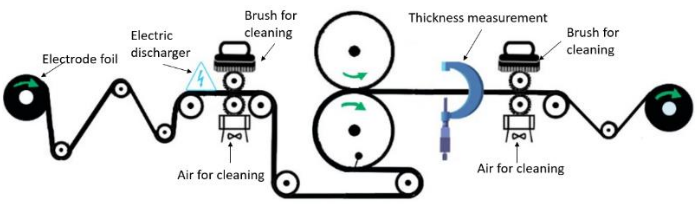


Figure 21: Schematic view of Calendering

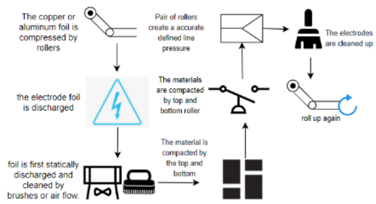


Figure 22: Process of Calendering

3.2.5.5 Slitting

Figure 23 shows the schematic procedure of slitting and Figure 24 shows the entire process together.

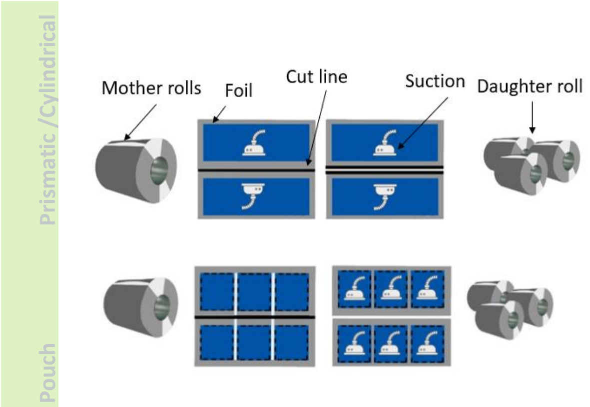


Figure 24: Schematic procedure of slitting process

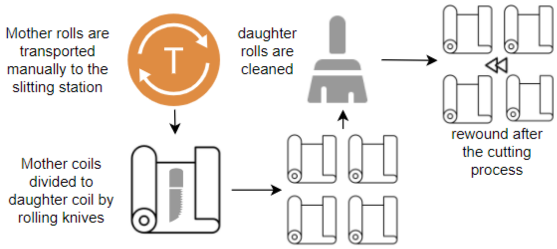


Figure 23: The process of slitting

3.2.5.6 Vacuum drying

This process is one of the most energy consuming/demanding ones. Some safety aspects should be considered. For instance, the interaction among Li salt, residual moisture, and LiPF6 might lead to the creation of HF gas leads to safety fluoride [22]. Figure 25 and Figure 26 shows the processes in two ways.

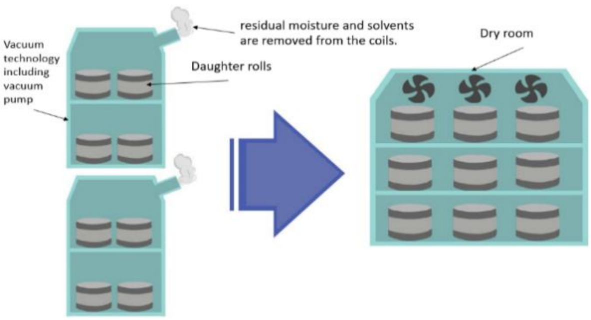


Figure 25: Schematic view of vacuum drying

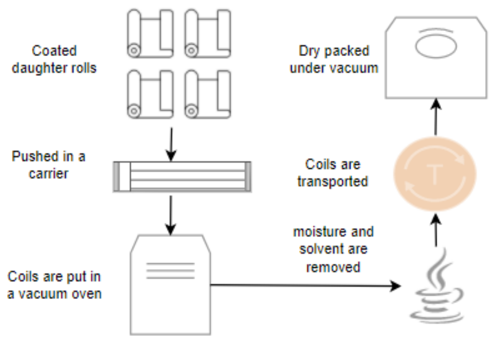


Figure 26: The process of vacuum drying

In addition, it should be considered that the low level of moisture is not the best solution for mechanical properties. Huttner et al analysed different time drying and suggested a fast argon post drying method at room temperature [23].

3.2.5.7 Stacking

Figure 27 shows the stacking process and Figure 28 shows the schematic vies of the stacking process. During the stacking process, the separated electrode sheets are stacked in a repeating cycle of the anode, separator, cathode, separator, etc.

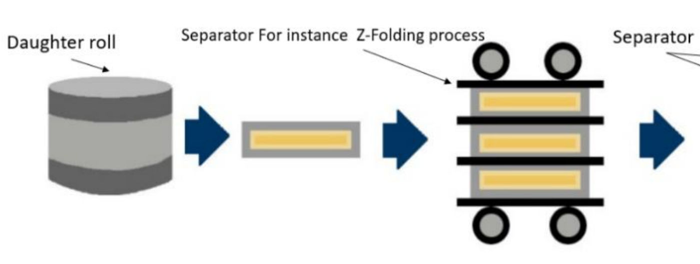


Figure 27: Schematic view of Stacking

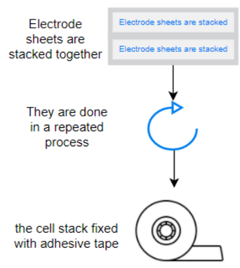


Figure 28: The process of vacuum drying

It should be considered that in contrast with the cell stack in the pouch cell, for prismatic and pouch cell the jelly roll is inserted into a robust metal housing. Therefore, the process is different for prismatic and cylindrical cells.

3.2.5.8 Welding

Scatters and battery cell types are important when joining technologies are used for battery welding. In short, ultrasonic welding is suitable for joining pouch cells, wire bonding for large modules composed of cylindrical cells, laser welding is good for cylindrical cells. as the welding occurs at the contacting surfaces locally, in contrast with laser welding in which a complete melting of the connector happens without considering the size of the battery. In addition, because each battery has its process, the related diagrams are so different for different technologies, so the following table illustrates some examples of different batteries for different technologies.

Vehicle	Cell type	Cell manufacturer	Joining technology	Ref
Tesla Model S 85 kW	Cylindrical 18650	Panasonic	Wire bonding	[24], [25]
BMW i3	Prismatic	Samsung SDI	Laser welding	[26], [27]
Nissan Leaf	Pouch	AESC	Ultrasonic welding	[28]
Chevrolet Bolt EV - Second generation	Pouch (12.7 by 17.7-cm)	LG Chem	Ultrasonic welding	[29]

Table 2: the different methods of welding for different applications

3.2.5.9 Enclosing

After the welding process and packaging the electrolyte is filling in and the cells are sealed.

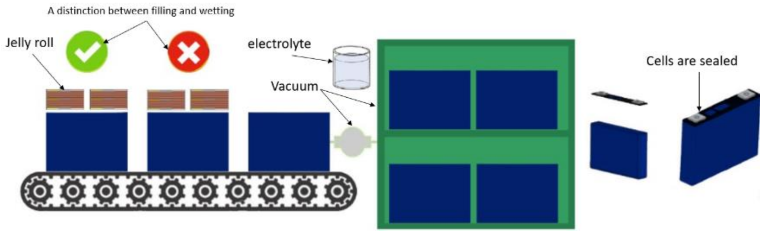


Figure 29: Schematic view of Stacking

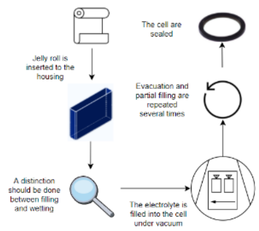


Figure 30: The process of vacuum drying

It should be considered that the prismatic and cylindrical cell winding process should be considered which is obligatory. Moreover, four pouch cells roll pressing should be added.

3.2.5.10 Formation

This process applies the first charging and discharging levels. Figure 29 and Figure 30show schematic and process of the formation process.

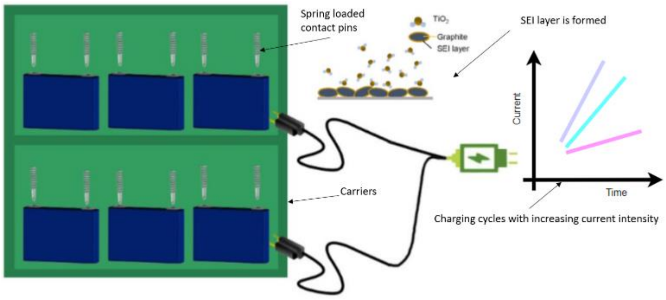


Figure 31. Schematic view of battery formation

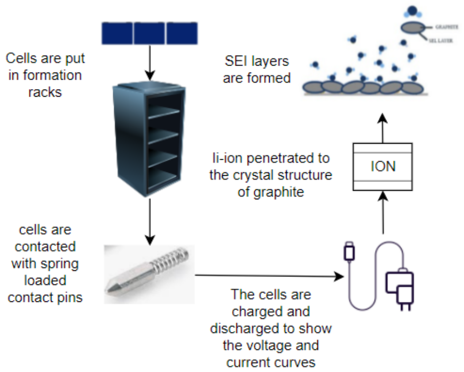


Figure 32. The process of battery formation

for pouching cells degassing process should be added to the process.

3.2.5.11 Aging

This step is applied for quality assurance, and this is the last step of battery manufacturing.

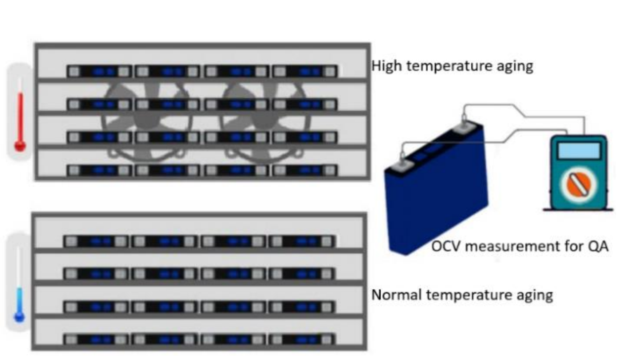


Figure 33. Schematic view of battery formation

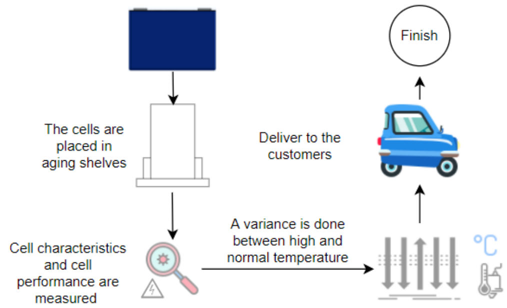


Figure 34: The process of aging

3.2.6 Conclusion

Even though several steps and practice may be introduced in order to improve the whole battery production process, the most-effective way is to concentrate on the most important parts of the process in terms of cost, time-consuming, and energy consumption performance.

As Figure 13 and Table 1 show the most important part of the process in terms of costs and time are aging and formation, therefore improving this step would improve the complete process. In terms of energy consumption, the most important parts are drying and solvent recovery.

So, applying different techniques and decreasing the energy consumption of this level would decrease the cost of the full process.

3.3 Battery application/integration

In the marine and offshore industry sector, the benefit offered by batteries is largely recognized. Specifically, lithium-ion batteries' dominant state leads regulatory entities such as American Bureau of Shipping (ABS) to provide requirements and reference standards for the installation on board of this technology and define a specific ESS-LiBATTERY notation that certifies its compliance **Error! Reference source not found.**. Such a certification guarantees the respect of requirements for BESS with a capacity greater than 25 kWh, which are used as 1) main source of power, 2) additional/supplemental source of power, and/or 3) emergency source of power. The main requirements are related to the battery system design and construction (including controls, monitoring systems, alarms, and Battery Management System (BMS)), and the battery installation (e.g. the battery space is defined and characterised by specific requirements which include ventilation, and fire fighting).

Similarly, other ship classification societies provided specific rules for li-ion batteries. E.g. the Italian ship classification society (RINA - Registro Italiano Navale) published an appendix to its Rules for the Classification of Ships - Part C Machinery, Systems and Fire Protection devoted to li-ion technologies with a capacity greater than 50 kWh **Error! Reference source not found.**. The same has been done from DNV GL in the case of batteries greater than 20 kWh **Error! Reference source not found.**.

In the following, a summary of the requirements for installing and managing batteries on board is provided. Notice that the summary is based on the prescriptions provided by RINA: *Rules for the Classification of Ships - Amendments to Part C, Effective from 1 January 2021, Appendix 2 Battery Powered Ships*; however, the requirements indicated in the other classification societies will also be analysed in the WP2 of this project.

3.3.1 Construction requirements

The supplier must provide evidence of compliance with the construction requirements defined by the Register and by current legislation.

In particular:

- The use of flame retardant materials
- Details on the internal pressure relief system: system arrangement and calibration.
- The presence of an overtemperature protection system.
- The precautions taken to avoid propagating the thermal runaway with confinement to the single module.
- Protection from direct contacts inside the battery box.
- The presence of a manual disconnection emergency command

3.3.2 Type approval

Each battery storage system, including the BMS, is subject to RINA (or other classification societies) conformity certification. This certification is stringent from the battery manufacturer's point of view.

3.3.3 Protections

Each battery system must be equipped with overcurrent and short circuit protection devices (fuses or multipole switches).

Moreover, each storage system must be divisible using disconnectors or switches with the function of disconnectors. An emergency battery disconnection command must also be implemented.

3.3.4 Control, monitoring and alarm system

The storage system, correctly designed and sized, must be controlled and managed by the BMS and PMS in order to avoid exceeding the limits declared by the manufacturer, including at least:

- Maximum and minimum temperature
- Maximum and minimum voltage
- State of Charge (SOC)

In the event of a BMS or PMS failure, the storage system must remain within correct and safe operating limits. To this end, an alarm and safety system must be provided.

The BMS and the PMS must be equipped with self-diagnosis systems that guarantee their correct functioning. In case of detecting a fault (which includes loss of power to the devices), an alarm must be activated.

3.3.4.1 Control and monitoring

The control system must manage the storage system to maintain its range of operation within limits set by the manufacturer. A load shedding signal must be provided.

Concerning the storage system only, the PMS must provide at least the following information:

- State of Charge (SOC)
- Power delivered
- Power available
- Available energy
- Estimate of the discharge time in the current operating condition
- Battery health status (SOH)
- Battery temperature
- Battery ambient temperature
- Battery temperature trend (trend)
- Battery cell temperature trend (trend)
- Status of the cooling system

The PMS will have to implement energy management functions (EMS functionality). Any scenario operational must be developed based on the required performance and operational limits in the safety of all components.

3.3.4.2 Alarm list

The alarms must be visual and audio-visual and must be reported near the workstations crew and command. Any event of malfunction of the storage system must provide an alarm.

Concerning the storage system only, an alarm must be provided and at least for the following events:

- Reaching the lower discharge limit of the battery
- Request for load reduction
- Security system activation
- BMS failure
- Cooling and ventilation system failure
- Battery protection intervention, including emergency release
- Ambient temperature limit exceeded
- Cell temperature limit exceeded
- Exceeding cell voltage limits
- Internal pressure increase

The list is not necessarily exhaustive and must eventually be completed based on specificities installation and specific requests.

3.3.4.3 Safety system

The safety system must include the self-diagnosis systems of BMS, sensors and devices equipment of the storage system (extractors, cooling).

The safety system is activated automatically in events that can cause conditions, danger and / or damage to the storage system.

The activation of the security system must include the activation of the appropriate alarms. Overriding security measures must not be allowed. The emergency disconnection command of the storage system must be implemented via an electric circuit independent from the control system. The emergency disconnection control must be accessible near the battery area and from the crew and command positions.

The sensors dedicated to the functions of essential, safety and emergency services must be independent from monitoring, control and alarm sensors.

3.3.4.4 Battery space

The battery space consists of the compartment (box, rooms) used for housing the batteries, specially and properly made and adequately ventilated and cooled in such a way as to maintain a specific set of environmental conditions.

The battery space must be made aft of the collision bulkhead. The battery space is normally unmanned.

The battery space must be dedicated to batteries only and allocated in such a way as to avoid exposure to excessive heat, extreme cold, splashes and nebulisations, shocks, vibrations and in general in all conditions that can reduce the degree of safety, performance or accelerate deterioration.

The ambient temperature of the battery room must be kept within the range specified by the builder. Storage systems used for propulsion and dynamic positioning services, or as one of the main power source units, must be installed in battery spaces within the boundary of the engine room or adjacent to it.

The danger area must be defined, in accordance with the required documentation.

The positioning of the battery space must result from the risk analysis. If the risk analysis requires it, e it is necessary to provide a room dedicated only to batteries. Cascading effects must be prevented.

Access to the battery room must be through self-closing doors. Alternatively, normally closed doors with alarm must be used.

Hazards arising from external events, such as the presence of fire and water, must be included in the analysis of risk. Appropriate countermeasures should be considered.

The battery space must be equipped with a fire detection and extinguishing system, suitable for chemical characteristics of the storage system, in accordance with the SOLAS regulations Reg. 11-2 / 10 and the FSS code. The extinguishing agent used specific to the type of batteries must be approved by manufacturer and must not produce corrosion or toxic or harmful substances.

The automatic release of the extinguisher is only acceptable for small and inaccessible battery spaces. Automatic activation must be confirmed by more than one sensor.

The ventilation system of the battery space must be:

- Independent from any air conditioning system
- Equipped with ventilation status indicator (running / not running) and ambient temperatures
- Equipped with safety control for automatic blocking in case of fire (confirmed by more than a sensor)
- Equipped with local control command available in case of control system failure automatic and / or remote.

In the case of a liquid cooling system, the ventilation system is dedicated to the extraction of possible noxious gases or vapours resulting from abnormal operating conditions.

If the risk analysis highlights the possibility that in the event of serious faults in the storage system, they can generate gas, then it is necessary that:

- At 30% of the Lower Explosive Limit (LEL) the battery must be disconnected, and an alarm activated.
- At 60% of the Lower Explosive Limit (LEL) all equipment electrical not classified as safe for the specific risk area must be disconnected and an alarm activated.

Failure of the gas detection system must trigger an alarm, without causing disconnection of the devices.

Ventilation must prevent the formation of an explosive atmosphere. The highest degree of gas emission of the single cell must be considered in accordance with the chemistry of the battery. Fans must be provided driven by motors classified as safe for the defined danger area, with delivery inlet in free air.

3.3.4.5 Test and Inspection

The storage system must be tested by the manufacturer.

Electronic equipment systems associated with the storage system must be suitable for the environment marine: tests must be conducted in accordance with Table 1, Part C, Chapter 3, Section 6 of the rules of RINA classification.

The storage system is subject to functional and safety tests in accordance with the IEC 62619 and IEC standards 62620, or in accordance with the equivalent national or international legislation.

For more details, with reference to the ABS “Guide for use of lithium batteries in the marine and offshore industries”, Feb. 2020.

Devices that regulate battery charge and discharge must be tested in accordance with Part C, Chapter 2, Section 7 of the RINA classification rules. In addition, the correct must be checked operation of the communication system with the BMS. The Test Program must contain the details of the relevant tests.

Tests must be conducted in accordance with the Test Schedule that must be submitted for approval, which includes functional tests (alarm system, security system, control system) e any further necessary tests identified by the risk analysis.

Battery health (SOH) tests must be conducted in accordance with manufacturer's instructions. After installation and after maintenance actions, scheduled checks, repairs or modifications that can alter the degree of safety of the system, the storage system is subject to at least the following checks:

- Visual inspection
- Operational tests
- Test of the alarm and security system
- Charge and discharge test
- Emergency detachment test
- Sensor testing, including simulation of parameter changes and sensor failure
- Communication system failure simulation
- Measurement of insulation resistance
- Correct operation of the ventilation, cooling, gas detection, fire detection system, fire extinguishing, etc.

3.3.5 Risk assessment

The risk assessment is a central and essential element for the realization of a system of edge that includes an electrochemical accumulation system of sufficient size to allow its use for propulsion services and as a major or alternative source of power.

The risk assessment must include:
- The assessment of risk factors
- The risk reduction measures adopted
- The actions to be implemented to keep the risk at an acceptable level

In particular, the risk assessment must clearly identify and express:
- The risk associated with fire (external to the batteries) and flooding
- The risk that (any) internal failure of the battery system could lead to malfunction essential services (including propulsion and manoeuvring) and emergency services.
- The measures taken to contain the Thermal Runaway and internal and external short circuits.
- The risk associated with the positioning of the batteries in relation to adjacent equipment.
- The measures taken to manage sensor, alarm, control and system failures of the battery storage system (including BMS and PMS).

3.3.5.1 The base case battery system

An example of risk assessment, for the thermal runaway and the BMS failure, executed considering the DNV regulation is proposed in the following **Error! Reference source not found.Error! Reference source not found.**.

Figure 35 depicts the considered study case. The base case battery system is in a dedicated room on board a hybrid diesel electric vessel. The vessel will use the batteries as a main source of power during normal operation.

The considered battery presents a liquid electrolyte. It is designed with a full module fire propagation protection. It consists of a module of 36 cells, each cell of 50 ampere hour (Ah). The cabinet and modules are protected from objects larger than 12.5 mm (IP20). The battery system is air cooled with ventilation directly into the battery space. The battery space has a ventilation system with dedicated ducts for air supply and air extraction. BMS and emergency shutdown system are independent from each other.

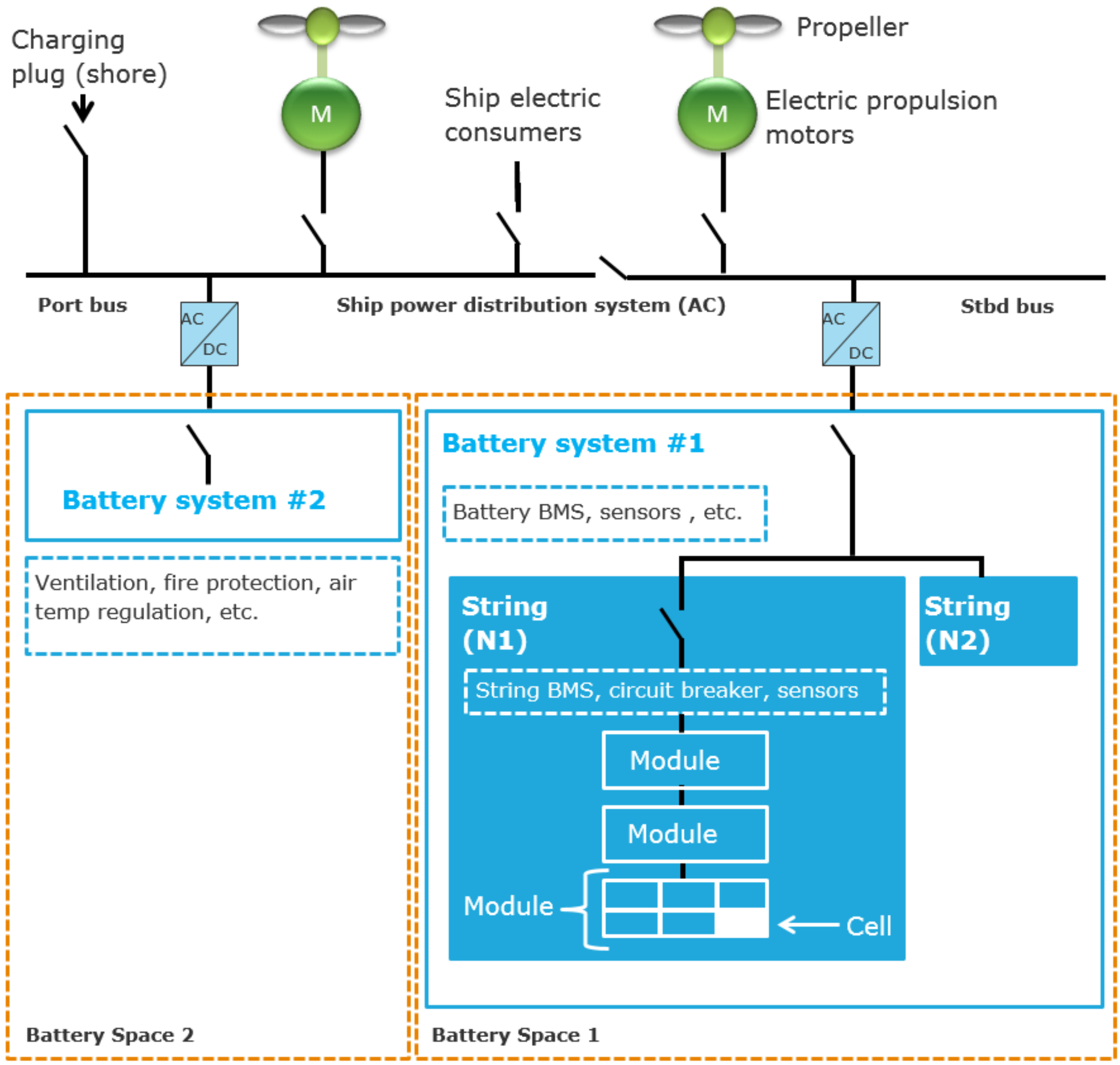


Figure 35 - Case study.

A Hazard identification (HAZID) is carried out for two of the more challenging problems in a battery system. The HAZID are thermal runaway and PMS and BMS failure. Causes, consequences, preventive safeguards and mitigating safeguards for each HAZID are listed in the following textboxes.

Thermal runaway (1.1)

Causes

- Internal short circuit
- Punctures cell
- Overcharging
- Excessive heat (external fire, loss of ventilation)
- Too rapid discharge (high current)
- External fire
- Failure of cooling system
- Long term undercharge of batteries
- External short circuit

Consequence

- Gas Development (flammable/explosive and asphyxiate/toxic)
- Fire
- Potential Explosion
- Potential Escalation to neighboring cells (module)
- Loss of battery power

Preventive safeguards

- PMS/EMS and BMS:
  * Temperature monitoring
  * Process control (voltage, current)
  * High/low voltage, High current, high/low temp alarm
  * Alarm if SoC below recommended value
- Independent Emergency Shutdown system
- Heat sink enclosure
- Air cooling of modules
- Operating procedures
- Cooling system redundancy

Mitigating safeguards

- Emergency Shutdown
- Module enclosure thermal design (insulation between modules)
- Independent room ventilation to open air
- Fixed fire extinguishing system in the battery compartment/space

Risk ranking:

3 – Unlikely

2 – Minor effect

PMS and BMS failure (3.3)

Causes

- Human error
- Software error
- Component failure
- Communication failure between converter and BMS/PMS

Consequence

- Overcharge
- Overdischarge
- Overvoltage
- Overcurrent
- Temperature increase

All the above are identified causes to Thermal Runaway and gas development

Preventive safeguards

- Operating procedures
- System integration tested and verified

Mitigating safeguards

- Independent Emergency Shutdown system
- Converter failure protection system
- Heat sink enclosure
- Air cooling of modules

Risk ranking:

3 – Unlikely

2 – Minor effect

Finally, all the identified hazards are listed in the risk matrix, Figure 36. The risk matrix is a visual representation of the frequency and consequence of the hazards.

Base case battery system		Likelihood				
		1	2	3	4	5
		Not expected	Very unlikely	Unlikely	Likely	Very likely
Consequence		$< 10^{-5}$	10^{-4} - 10^{-5}	10^{-3} - 10^{-4}	10^{-2} - 10^{-3}	10^{-1} - 10^{-2}
1	No effect					
2	Minor effect			1.1, 3.3		
3	Moderate effect					
4	Major effect					
5	Hazardous effect					

Figure 36 - Risk matrix.

3.4 Recycling

3.4.1 Introduction

Li-Ion batteries (LIBs) contain hazardous heavy metals and toxic chemicals that represent a danger to our ecosystem. In other words, due to the excellent electrochemical performance, LIBs have received an increasing attention for energy storage applications. The rapid growth trajectory in LIBs battery manufacturing will result in a huge amount of spent LIBs reaching their end of life. Therefore, with the rapid growth of LIBs for energy storage application, a lot of attention has been paid to the recycling and reuse of spent lithium-ion batteries due to the sustainability, procurement, and resource circulation Reuse of batteries can be useful, and beneficial for circular economy [30]. Recycling LIBs can secure raw materials supply for energy storage systems; consequently, reducing energy usage and environmental emission impact from battery life cycle.

3.4.2 Purpose of the section

To have a better understanding of LIB recycling and its potential both worldwide and on European level, the current situation both on economic and technical level should be considered.

3.4.3 Chapter structure

Following aspects are described in this report:

- Cost structure of the different materials of Lithium-Ion cell
- Recycling in the LIB material flow and recycling technologies
- Recycling revenues for different materials
- Occurring costs for the recycling processes
- Recycling in Europe and Outlook in the Future

3.4.4 Economics of Recycling

To consider the economic side of recycling, both the cost structure of the LIB cells and the recycling costs should be analyzed. The cell chemistry in SEABAT has not yet been defined. Therefore, the cost structure of cells is explained using some examples of cell chemistries (NMC 811, NMC 622, LCO, NCM111, NCM 523).

3.4.4.1 Cost Structure of LIB cell

The costs of LIB are mainly governed by the raw material situation and the use of cell chemistries with higher energy densities. The new generation of LIB will mainly use higher nickel and lower cobalt content like NMC 622 or NMC 811. Cobalt-free batteries like NCA and LNMO are thus gaining in importance. Nevertheless, driven by the increasing demand for batteries, the demand for raw materials will continue to rise, which might lead to price fluctuations.

Due to the introduction of Cobalt fee batteries, Nickel metal costs have started to increase in the last 5 years. The development of Cobalt and Nickel in the last 10 years is shown below. (Figure 37)

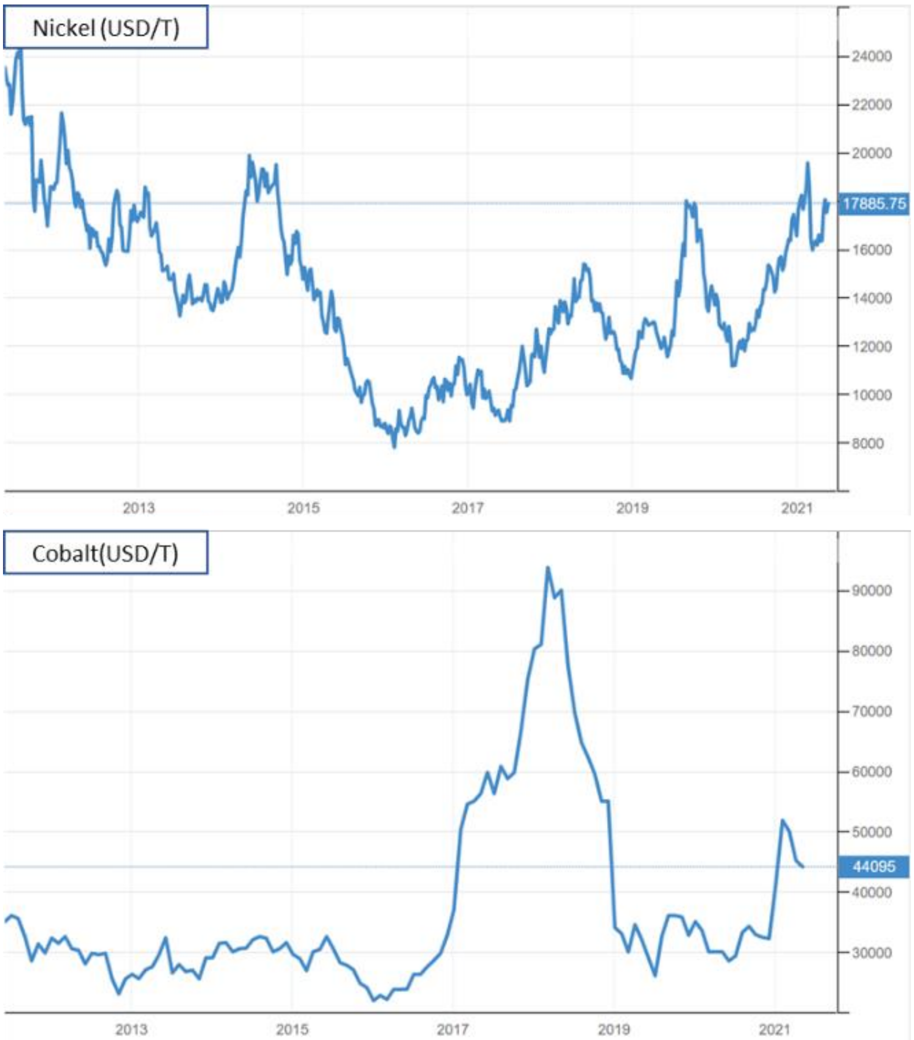


Figure 37: Nickel and Cobalt price fluctuations in the last 10 years in USD/T [30]

Based on 2018 raw materials price levels, the cost structure of materials is showcased for an NMC 811 cell [31]. As shown below (Figure 38), the cost of the cathode material accounts for almost a quarter of the battery cell.

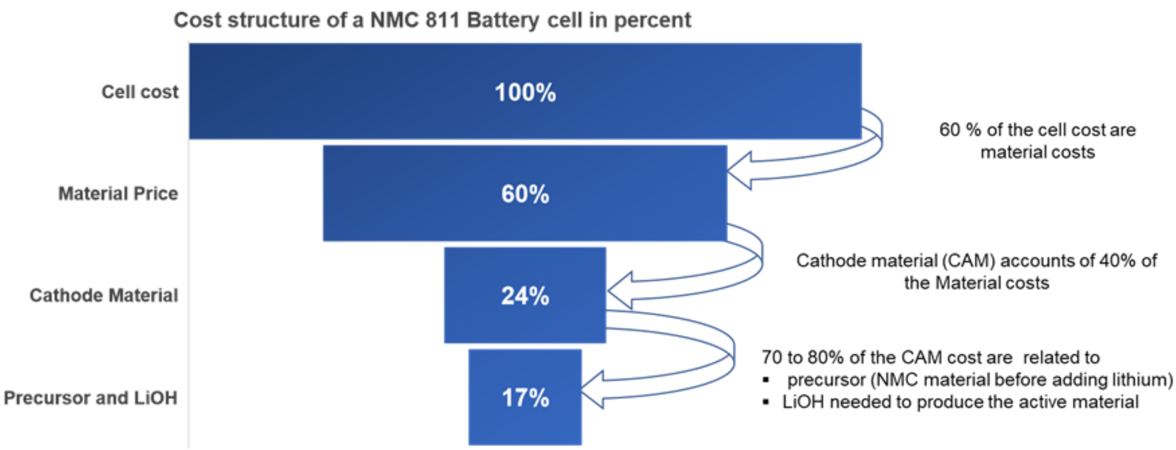


Figure 38: Cost structure of a NMC 811 battery cell in percent

The cost structure [32] of a cell in 2020 and the influence of price fluctuations can be seen in the Figure below (Figure 38). The cell costs are modeled based on a theoretical 10 GWh non-integrated plant. Both graphs show that the cost of the cathode material and cathode process account for over 50% of the total cost. Based on November 2020 raw material costs, the cell cost is $87.2 kWh. Considering the highest price level of raw materials in the last 10 years for Li, Co and Ni, the cell cost increases from $87.2/kWh to $119/kwh. (+36.4 %)

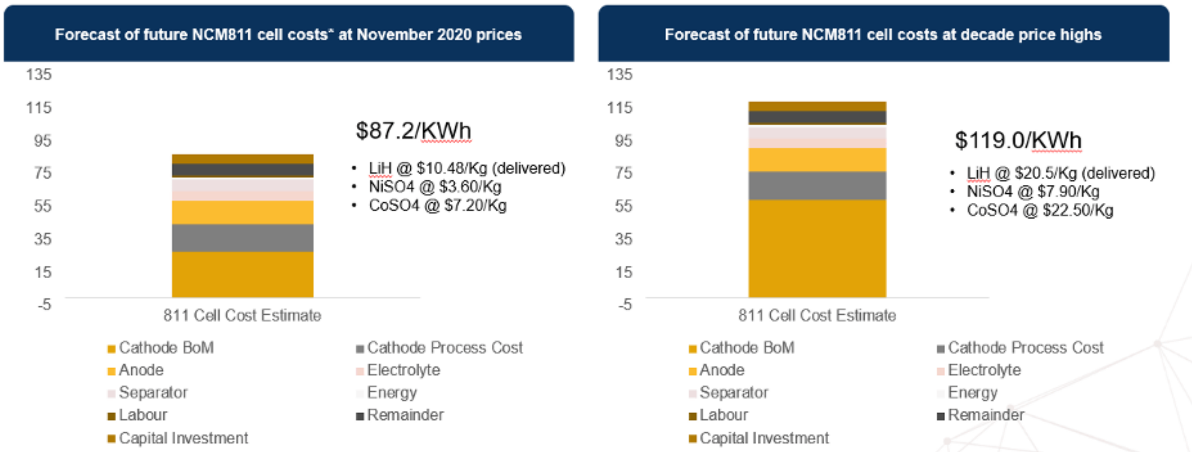


Figure 39: NMC 811 cell costs depending on raw material prices (November 2020 prices and decade high prices) [32]

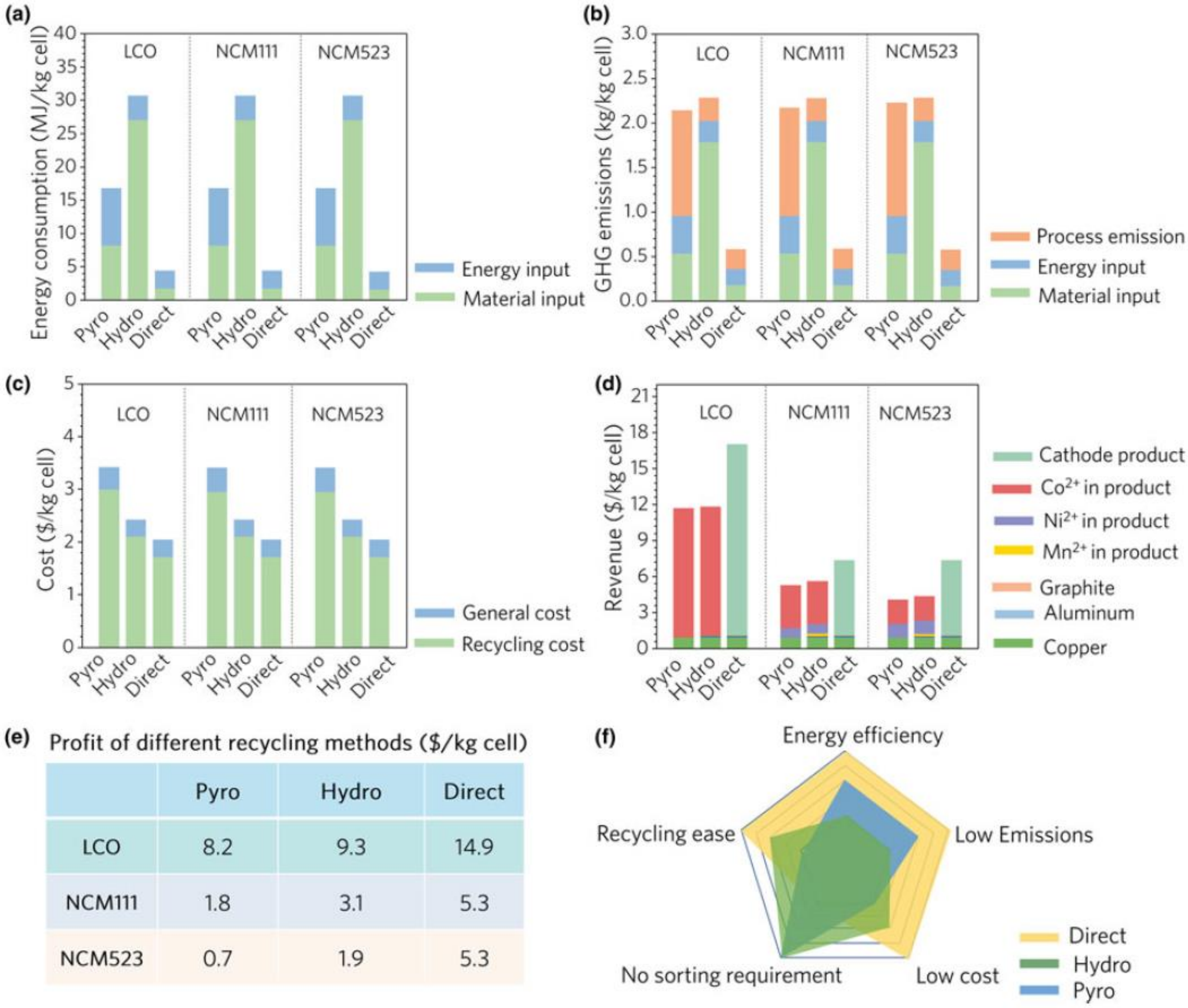
Please note that, high proportion of current recycling processes is focused on reclaiming the cathodes materials and less effort on recycling other materials. Therefore, recycling can be economically profitable based on cathode materials such as Lithium Manganese Oxide (LMO) cathode batteries from $860 per metric ton to $8900 per metric ton Lithium Cobalt Oxide (LCO) cathode batteries. [33]

3.4.4.2 *Recycling Cost and profitability*

Used LIB contains both highly valuable materials (such as Li, Ni and Co) and elements with low recovery values (such as Fe, Al, and P). While recovering valuable metals from cathode material is economically attractive and analyzed, the recovery of anode materials and electrolyte is less reported. [34]

A recent study (state 2020) directed by the *Department of NanoEngineering at the University of California* has investigated the economic and environmental analysis of recycling of three different cell chemistries (LCO, NCM111, NCM523). [35] The different recycling methods such as pyrometallurgy, hydrometallurgy and direct recycling are considered. Following aspects are investigated:

- Energy consumption (MJ/kg cell)
- GHG emissions (kg/kg cell)
- Recycling Cost ($/kg cell)
- Potential revenues from outputs produced ($/kg cell)
- Profitability of the different recycling methods ($/kg cell)



	Pyro	Hydro	Direct
LCO	8.2	9.3	14.9
NCM111	1.8	3.1	5.3
NCM523	0.7	1.9	5.3

Figure 40: Economic and environmental analysis of different recycling methods based on 1 kg of LIBs across different cathode material chemistries [35]

Roland Berger conducted a study in 2018 to demonstrate the economy of battery material recycling [31]. The figures below have been generated based on the above-mentioned study. Based on a BEV pack of approximately 60 kWh (NMC 622 chemistry), a study to break down the weight of the different materials that can be recovered is shown in Figure 41. Steel, electronics, aluminum, copper and plastics can be recovered through mechanical treatment. Non valuable or/and contaminated materials generate negative revenues.

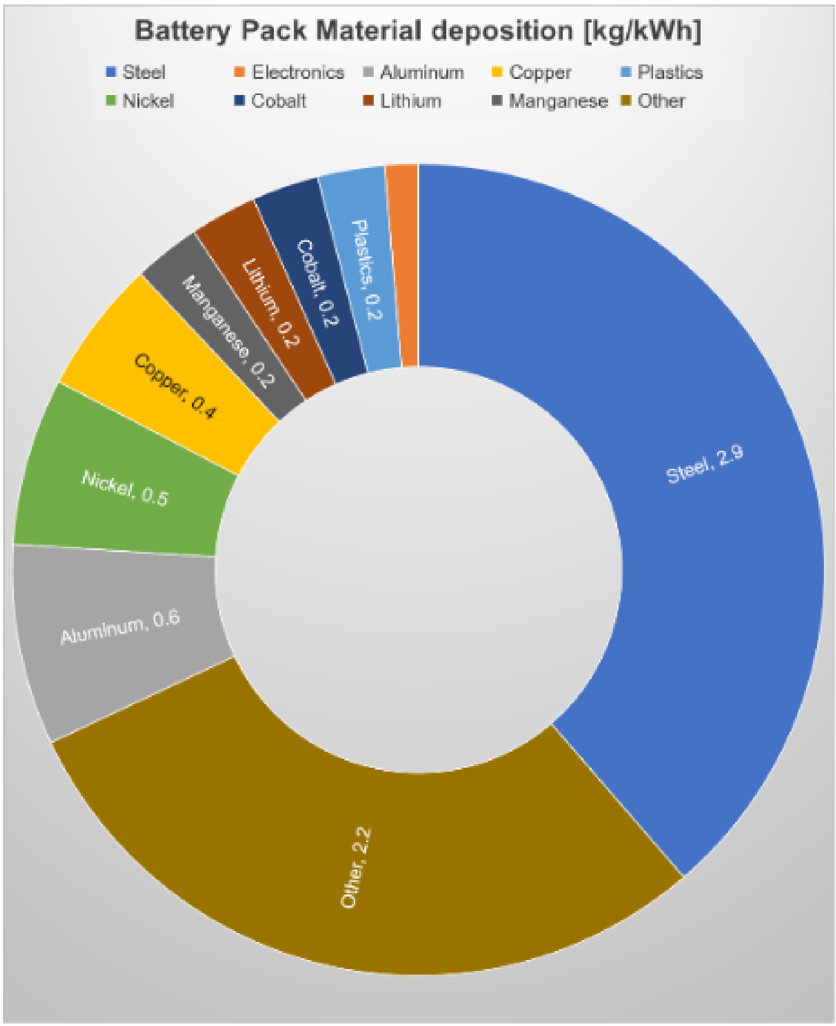


Figure 41: Battery pack material deposition in kg/kWh for a NMC 622 cell chemistry

Motivated by the increase in the demand of raw materials like lithium, cobalt, manganese and the associated risk in the supply chain, recycling is gaining in importance lately. Recycling can provide protection against uncertainties in raw material prices for LIB. Depending on the recycling technology and raw material prices, recycling may lead to income at the end of the battery lifetime.

Two important factors influence the profitability of recycling:

- Recycling values (Euro/kWh): generated revenues from recycling materials
- Recycling cost (Euro/kWh)

3.4.4.3 Recycling values

Due to the different recycling technologies and different cell chemistries the profitability of recycling may vary. This is reflected in the Lithium, Cobalt, Manganese and Nickel recycling values (Figure 42). Two methods are used in the study to calculate the price of the raw materials. [31]

- **Method 1**: Considering a 95% recycling efficiency and a material price estimated at 70% of 2018 stock price, the recycling revenue price of the above-mentioned materials is 11 Euro/kWh.
- **Method 2**: Considering a hydrometallurgical recycling of NMC 811 and LiOH at approx. 95% efficiency, revenues at 25 Euro/kWh can be achieved.

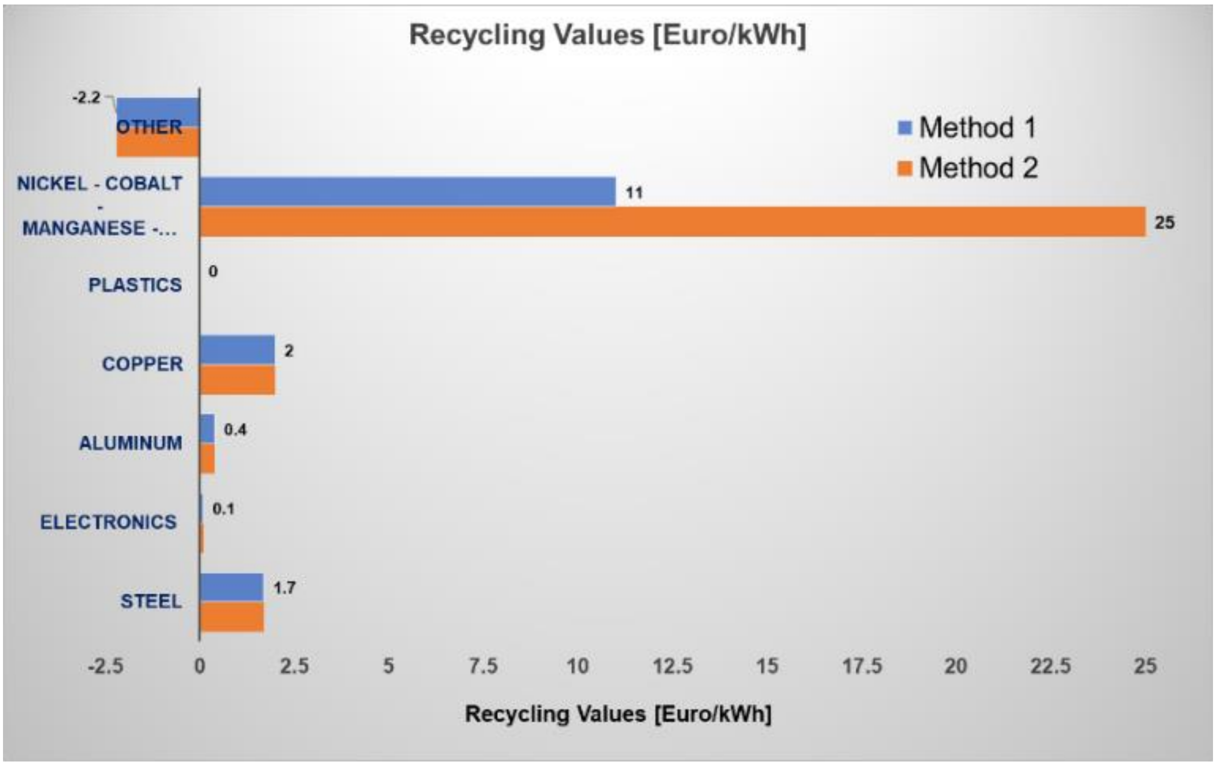


Figure 42: Recycling values of different battery materials in Euro/kWh

Based on both methods, recycling revenues between 13 and 26 Euro/kWh can be gained from material recovery. This indicates that the economics of recycling can be viewed from different perspectives.

3.4.4.4 Recycling costs

Besides the metallurgical processes, battery recycling generates other costs related to disassembly, logistics and mechanical treatment. The different recycling processes are discussed later in detail. The costs for these steps are shown in Figure 43. The values are calculated in Euro/kWh. For a battery pack based on NMC 811 chemistry. A total between 8 and 11 Euro/kWh is predicted.

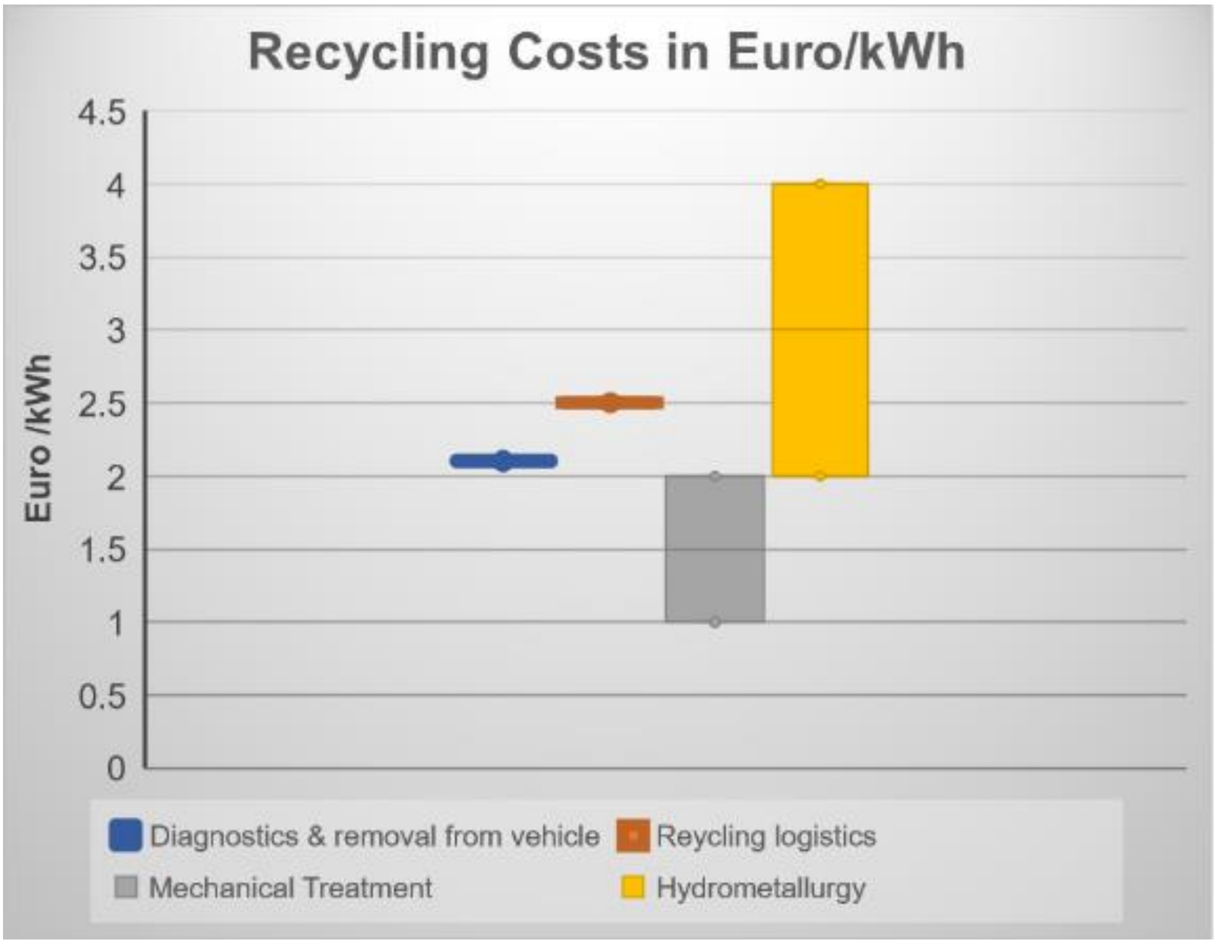


Figure 43:Different recycling cost for LIB cell based on NMC 811 chemistry.

3.4.4.5 Recycling profitability

To calculate the profitability of recycling, both the value of the recovered materials and the recycling costs are needed:

$$Recycling\ profitability\ = Revenues\ from\ Materials - Recycling\ costs$$

The potential net gain from recycling is between 5 and 15 Euros/kWh. Considering a vehicle with 60 kWh (*e.g., Opel Ampera-e),* between 300 and 900 Euros can be saved. With an increasing recycling in the future, different recycling costs, like for logistics or removal from vehicle, might decrease, which will enhance the attractiveness of the material recovery. Toward the end of 2020 the market average of battery pack sits at 116 Euro/kWh [36]. Based on Roland Berger [31] calculation between 4% and 13 % of the Battery pack can be saved, which highlights the promising potential of Recycling in LIB.

3.4.5 Recycling technology processes

Recycling's economic potential depends heavily on the recycling technology processes and their efficiency. This section reviews the state-of-the art processes for LIB recycling and gives an overview about the main recovery processes. The main challenge resides in improving the effectiveness of the processes and reducing the environmental pollution during processing to make recycling more profitable and attractive in the long-term. Processes for metal recycling can be divided into three steps:

- Pre-treatment process
- Metal-extraction process

- Product process

A general schematic of the processes for recycling of LIBs (based on [37] and [31]) is shown below (Figure 44)

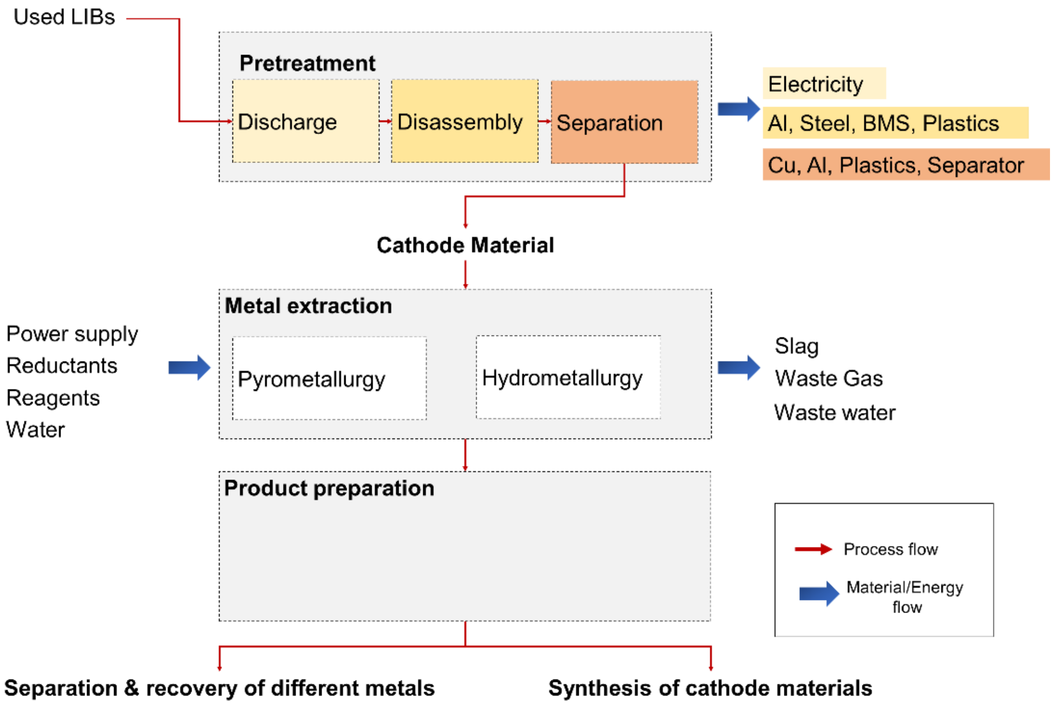


Figure 44: Schematic of the processes for LIB recycling

3.4.5.1 Pretreatment

First LIBs are discharged through immersion in a salt solution to prevent short circuiting or combustion. Next, the LIBs are dismantled manually or mechanically to separate cathode, anode, and other components. To separate the cathode material from the foil, different methods can be applied. The advantages and disadvantages of the different pretreatment methods are summarized in [34] and are shown below.

Table 1: Advantages and disadvantages of different pre-treatment methods [34]

Technology	Advantages	Disadvantages
Solvent dissolution	High separation efficiency	High cost of solvent, environmental hazards
NaOH dissolution	Simple operation, high separation efficiency	Difficulty in aluminum recovery, alkali wastewater emission
Ultrasonic-assisted separation	Simple operation, almost no exhaust emission	Noise pollution, high device investment

Thermal treatment	Simple operation, high throughput	High energy consumption, high device investment, poisonous gas emission
Mechanical methods	Simple and convenient operation	Poisonous gas emission, cannot separate all kind of components in spent LIBs completely

Mechanical treatment is an effective separation method and involves crushing, magnetic separation and sieving. [34] Increasing the automation and efficiency in dismantling the spent LIBs during the pretreatment process could further promote the recycling industry.

3.4.5.2 Metal extraction

Metal extraction involves one or more methods and is a significant part of the recovery process. The objective of metal extraction is to transform the solid state of batteries into their alloy form or solution state [34] and to break down the physical and chemical structures of materials. This will ease the separation and recovery of the metals. A general overview of the process workflows for primary manufacturing and the conventional recycling methods as well direct recycling is shown below. [35]

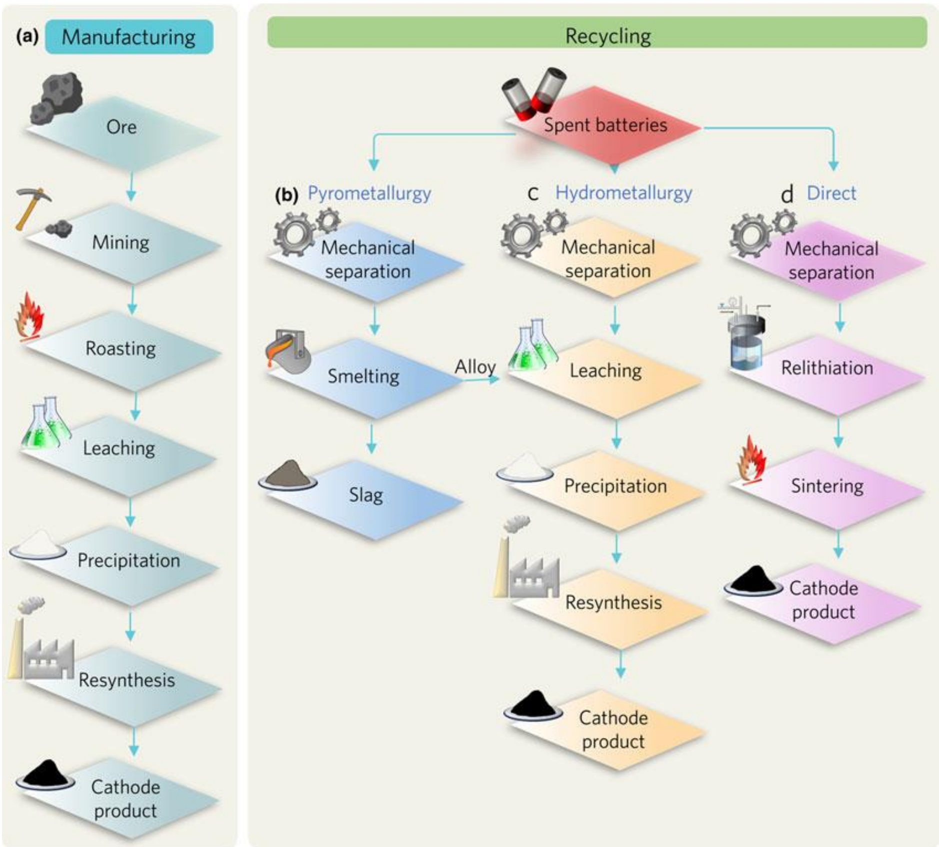


Figure 45: Process workflows for primary manufacturing, conventional recycling methods for the extraction of critical materials, and direct recycling methods [35]

The metallurgical process is dominated currently by two main extractive processes:

<u>Pyrometallurgical process</u>

The pyrometallurgical process is a thermal treatment that enables the recovery of valuable metals. This method enables the processing of different cell chemistries at the same time and enables thus simplified logistics. Through smelting Nickel, Cobalt and Copper can be recovered in a pyrolysis process in the form of concentrated alloy of high purity. On the contrary, Lithium and Manganese cannot be recovered efficiently from the slag.

The recycling of these materials is thus not the most economical. [38] A typical pyrometallurgical process is high temperature smelting reduction. This method is simple, but it leads to the loss of Lithium and it is not environmentally friendly due to its high energy consumption. [34] A combined metal extraction method developed by the Belgian company Umicore combines the pyrometallurgical and hydrometallurgical processes. [34]

Hydrometallurgical process:

Hydrometallurgy refers to the extraction and refining processes, such as leaching, that exploit the specific solubility of different materials and involves the use of aqueous solutions to extract metals from ores. Through leaching the metallic components and the recycled metal solutions are dissolved. Leaching agents could be inorganics acids, organics acids and ammonia-ammonium salt systems. [34]

In contrast to pyrometallurgy, high recovery rate for Lithium and Manganese are possible. Due to the high recovery rate and high purity of the outcome, hydrometallurgical process is a very promising method.

High metal-leaching efficiencies could be achieved using inorganic acids. However, this method will produce acidic wastewater and harmful gases (such as NO_x). [34] An economically effective approach combines reduction leaching with selective precipitation, as described in [39]. The following efficiencies could be attained (materials in their precipitate form)

- Cobalt: 97 %
- Nickel: 96%
- Lithium: 93 %

In the table below the two main metal-extraction processes are compared.

Other methods

Since pyrometallurgy uses a lot of energy and implies a high loss rate of materials, and hydrometallurgy's consumptions of reagents is very high, new environmentally friendly recycling methods, such as Bio-metallurgy have been investigated lately.

Bio-metallurgy: Inorganic and organic acids are produced by microbial activities. Even though Bio metallurgical processes are cost-effective due to their low energy consumption, the leaching efficiency is low, the leaching time is long and the bacteria are hard to cultivate. [40] Other methods such as Mechanochemical process are further described in [34].

Table 2: Comparison between Pyrometallurgy and Hydrometallurgy [40]

Process	Advantages	Disadvantages	Environmental hazards
Pyrometallurgy	• Great capacity • simple operation	• High temperature • High energy consumption	Waste gas, dust

		• Low metal recovery rate	
Hydrometallurgy	• Low energy consumption • High metal recovery rate • High product purity	• Long recovery process • High chemical reagents consumption	Wastewater

The figure below (Figure 46) shows the recovery rate at the end of recycling process for different chemical components and different hydrometallurgical approaches used by leading Asian players. The recovery rates are measured at the end of the recycling process. [34]

14

Chemical component	Li	Ni	Co	Cu	C
Pyrolysis	0%	40 – 60%	40 – 60%	n.c.	0%
Pyrolysis - Hydrometallurgical	50 – 60%	> 95%	> 95%	> 95%	0%
Mechanical - Pyrolysis (slag)	0%	40 – 60%	40 – 60%	n.c.	0%
Mechanical - Hydrometallurgical (black-mass)	> 90%	> 99%	> 99%	> 99%	0%

Figure 46:Recovery rate for different chemical components and for different hydrometallurgical approaches [37]

3.4.5.3 *Production preparation process*

The two main goals of the production preparation process [40] are:

- Separation and recovery of valuable metals: Valuable metals from leachate are extracted through solvent extraction, chemical precipitation, and crystallization.
- Synthesis of the cathode material: To reduce the cost of separating Ni, Co and Mn from leachate, the precursor material is prepared through adjusting of the leaching solution. The precursor material is then further synthesized by means of co-precipitation or sol-gel. Co-precipitation is a simple and most common used method and, but it often leads to impurities. The sol-gel method operates at low temperatures and has short reaction time. However, the reproducibility of this method is low.

3.4.6 Recycling and circular economy

The chapter presents an overview of the circular economy concept for batteries and illustrates a possible model for moving from a linear economy to a circular economy. The circular economy key features for batteries are the second life applications and the market size. The European community is pushing toward the circular economy and the analysis of the potential reuse of exhaust batteries coming from automotive applications. After an introductory analysis, a special focus for the marine sector is proposed. The marine second life battery sector is today in its very early phase, and the estimation and forecast of the possible second life market is of interest.

- Market size and costs for repurposed EV batteries: shows possible applications of second life batteries and the market potential.
- **Example of European project:** illustrates a European project, which analyses the feasibility of second life applications.
- **Focus on second life battery from marine :** is focused on marine batteries. Based on the estimation carried out in the WP1, the second life battery energy availability and market size for the marine sector are estimated.

3.4.6.1 From linear to circular

The 9R model [41] is a useful framework to show the journey from linear to circular economy for products. The three key principles of the circular economy are in the 9R model are listed below:

- Design out waste and pollution (R0 to R2: smarter product use and manufacture)
- Keep products and materials in use (R3 to R7: extend lifespan of product and its parts).
- Recycling and recover of materials (R8 to R9: all batteries may be recycled).

The diagram Figure 47 describes the 9R model.

Circular Economy	Smarter Product Use and Manufacture	R0 Refuse	Make products redundant by choosing circular products that possess some or all of the qualities of the 9R's
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacturing or use by consuming fewer natural resources and materials
	Extend Lifespan of product and its parts	R3 Reuse	Reuse by another consumer a discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective products so it can be used with its original function. Generally has not been tested and may not include a warranty
		R5 Refurbish	Restore a product and bring it up-to-date or restore functionality. Includes testing for defects prior to resell and usually includes a warranty
		R6 Remanufacture	Rebuilding of a product to original specifications by exchanging worn parts with repaired, used or new parts. The product or machine should perform as a new one and includes a warranty
		R7 Repurpose	Use discarded products or its parts in a new product with a different function
	Useful application of materials	R8 Recyclable Resource Recovery	Process materials to obtain the same (high grade) or lower grade quality
Linear Economy		R9 Recover	(1) Recover or 'cannibalise' from damaged products for the reuse of parts in order to facilitate remanufacturing or refurbising activities. (2) Incineration of material for energy recovery

Figure 47 - 9R model.

With focus on batteries, one of the main purposes of the transition from linear economy to circular economy is giving batteries a second life.

Repurposing batteries (R7) simply means reusing them in another application. Large Electric Vehicle (EV) batteries may have in the order of 70% - 80% of their capacity remaining when they reach the end of their useful life in a vehicle after 10-15 years. This presents a significant opportunity to repurpose EV batteries in other applications that do not require such high levels of 'cycling', or capacity [41]. These applications include:

- Replacing less-efficient assets such as old combined-cycle gas turbines.
- Use in stationary storage.
- Use in other mobile applications.
- Use as grid stabilizers.

3.4.6.2 Market size and costs for repurposed EV batteries

There are a significant number of current and potential future applications/use cases for batteries that have been used in the EV sector.

The energy storage will significantly increase over the next ten. The global energy storage market is expected to rise to 125 GW / 304 GWh by 2030, [42].

It is possible that a large share of this demand can be potentially met by second life batteries from EVs. However, the proportion of batteries which may be available for this use at end of life depends to a great extent on the ownership and usage case during first life. For example, if an EV owners owns their battery and uses it until it has reached an unacceptable SOH, it may not be suitable for re-purposing. However, if the battery is leased, and will be replaced at 80-90% SOH, then this could much more easily be re-purposed. Figure 48 present forecast of used battery availability, the light blue bars represent the annual gross GWh of used EV battery output, the blue line represent the cumulative energy curve of EV battery output, and the dashed line represent the cumulative curve of reusable batteries for stationary storage.

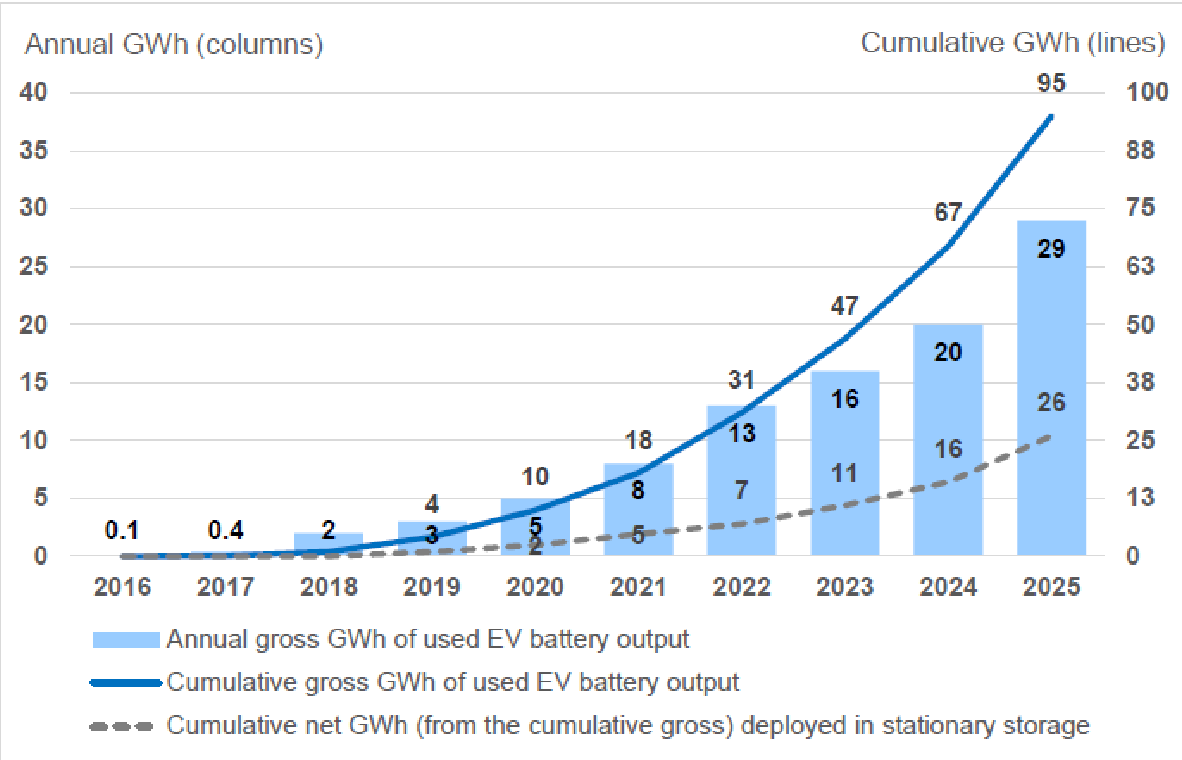


Figure 48 – Forecast of used battery availability.

This feedback also appears to be supported by analysis from NREL (National Renewable Energy Laboratory – USA), they expect most batteries to become available for second use at the end of the expected EV service life of ~15 years. NREL studies show that these batteries can retain as much as 70% of their initial capacity and potentially continue to operate for another 10 years in second use as energy storage for utilities—translating into a total service life of up to 25 years [43].

3.4.6.3 Costs

In addition, the following economic figures in Table 3, have been identified for the potential market capacity and value for repurposed battery energy storage from a range of sources. The potential cost/price of such repurposed batteries should also be compared with future projections in new battery costs. The potential risk is that repurposed batteries may struggle to compete on a purely economic basis with new batteries should the costs of the latter continue to decline rapidly [43].

In Table 3 are reported the potential prices of second life batteries. The prices are related to studies from the literature.

Table 3 - Summary of the potential market price for repurposed batteries.

Source	Capacity/market size	Value or Price of repurposed batteries
How to Save Money and Clean the Grid with Second-Life Electric Vehicle Batteries [44]	N/A	Price of re-purposed batteries estimated at $38-132/kWh (may vary depending on application).
Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves [45]	25 GWh of second-life batteries entering the German market by 2025	Estimated at €150/kWh ($175/kWh).
Liebreich and McCrone: Electric vehicles – It's not just about the car [46]	N/A	$49/kWh to repurpose [by 2018], compared to the current new stationary battery price [in 2016] of around $300/kWh.
China's Giving Batteries a Second Life [47]	N/A	Chinese refurbishes will pay $4/kg for batteries with reuse potential; a battery more suited for recycling will go for as little as $1.50/kg.

3.4.6.4 Recycling

All batteries may be recycled regardless of chemistry. In most countries, battery producers must sign up to a battery recycling scheme. Facilities used for the recycling of lithium-ion batteries exists. The value of the recycled materials more or less pays for the cost of the recycling. It has been suggested that 72-97% by weight of a lithium-ion battery may be recyclable.

In addition, lithium-ion battery recycling has proven to be feasible, with several companies providing this service. The current focus is on aluminium and copper recovery, as this provides the greatest revenue stream, with the low price of mined lithium proving to be highly competitive – as well as challenges with regard to quality. The full potential of such processes is limited primarily by the current low inflow of recycled, used or decommissioned batteries – refurbishment is presently a more common end-of life service resulting in an even better environmental footprint.

3.4.6.5 Example of European project

Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB) an exploratory project led by Joint Research Centre (JRC) under its own initiative in 2016-2017, aims at assessing the sustainability of repurposing EV batteries to be used in energy storage applications from technical, environmental, and social perspectives. Information collected by stakeholders, open literature data and experimental tests for establishing the state of health of lithium-ion batteries (in particular LFP/Graphite, NMC/Graphite and LMO-NMC/Graphite based battery cells) represented the necessary background and input information for the assessment of the performances of EV battery life cycle. Renewables (photovoltaics) firming, photovoltaics smoothing, primary frequency regulation, energy time shift and peak shaving are considered as the possible second-use stationary storage applications for analysis within SASLAB. Experimental tests were performed on both, new and aged cells. The majority of aged cells were disassembled from a battery pack of a used series production EV. Experimental investigations aim at both, to understand better the performance of cells in second use after being dismissed from first use, and to provide input parameters for the environmental assessment model [48].

3.4.6.6 Second-use applications

In the SASLAB project the following second use applications has been assessed.

3.4.6.6.1 Peak shaving and self-consumption of renewable energy

It is an energy storage service used to shift electricity demand from on-peak to off-peak periods. It requires a duration of discharge of the ESS during the on-peak period on the order of 2 to 12 hours and is intended to recharge in the off-peak period to be available again the following day. Within this time frame (day), the peak shaving service can be used for shifting electricity demand to relieve peak demand charges, thus ensuring a saving for the customers. Also, the peak shaving service can be used to increase the self-consumption of renewable energy. In this case the PV energy that is exceeding the permitted feed-in limit is stored in the battery avoiding the loss of such energy [48]

3.4.6.6.2 PV smoothing

PV smoothing is a power service performed by ESS to mitigate rapid fluctuations in photovoltaic (PV) power output that occur during periods with transient cloud shadows on the PV array. The ESS is adding power to or subtracting power from the output of a PV system in order to smooth out the high frequency components of the PV power. The purpose of PV smoothing is to mitigate frequency variation and stability issues that can arise at both the feeder and transmission level in high penetration PV scenarios to help meet ramp rate requirements [48].

3.4.6.6.3 Primary frequency regulation

Frequency regulation is primarily a power service. Grid must maintain balance between load and generation especially with the increasing penetration of small-scale intermittent distributed energy resources such as solar/wind that poses frequency regulation problems due to the reduced system inertia. Regulation of electric power frequency is provided by increasing or decreasing the amount of energy injected into the grid or the amount of load on the grid in a time frame that ranges between fraction of seconds to few minutes [48].

3.4.6.7 Results of the assessment

Concerning the adoption of a repurposed battery for a peak shaving application in a grid-connected office building in Italy, the Life Cycle Assessment (LCA) results in the SASLAB project showed that a repurposed LMO/NMC battery is environmentally beneficial only if it replaces a fresh battery (either a LMO/NMC) **Error! Reference source not found.**. The addition of a repurposed battery in a building in which no batteries were previously used does not entail benefits. Note that results of the LCA are affected by the energy mix used in the assessment, in particular to the feedstock providing the energy during the peak hours. In specific Countries, where differences in feedstocks are relevant, this is a relevant aspect to be assessed in the LCA. If repurposed batteries are used to increase the PV self-consumption of a residential dwelling, higher benefits are observed compared to the previous application. The adoption of a repurposed battery in place of a fresh one (either LMO/NMC) entails environmental benefits due to the avoided battery manufacturing (in case of fresh LMO/NMC battery).Moreover, in case of stand-alone houses, where the energy not provided by the PV installation is provided by generators, the adoption of a repurposed battery is even more convenient [48].

3.4.6.8 Focus on second life battery from marine applications

After the battery has degraded to the point where it no longer fits the operational profile of the vessel, it will (in most cases) have capacity left and may be refurbished for reuse and get a second life. The industry is still too early in the process to see maritime batteries available for second life applications. Batteries which would be potentially viable for second life will still have storage capacity and can be used.

Second life is often discussed for automotive batteries and has significant interest from major car manufacturers. However, these batteries are small and require integrating and controlling many thousands of them for a grid application (for example). In contrast, a maritime system is already likely on the MW-scale and thus fewer systems would need to be integrated [49]**Error! Reference source not found.**.

It is a significant challenge for 2nd life batteries to control the individual modules if different battery systems are combined because they will have been used differently and thus have different states of health. Would-be adopters as well as manufacturers may be hesitant to the use of secondary material as the battery degradation and the current state of the battery may be challenging to assess [50].

The end-of-life cycle of batteries is an important life-cycle phase. Batteries which have been used on board ships but are too used to satisfy classification and safety requirements still have storage capacity and can be used for stationary applications.

In the Marine Battery Forum several battery producers indicate that while grid stabilization is promising on a technical level, there needs to be more safety procedures and infrastructure in place for batteries which have reached the end of life for the use for which they were designed. Currently, one of the barriers is that a battery manufacturer can be reluctant to allow the use of used battery for grid services, due to responsibility issues in the case of potential accident. In addition, a non-standardized mechanical shape and a non-standardized control interface makes it more technically challenging and thereby more expensive to use old batteries for terrestrial application [50].

Marine Battery Forum members also indicate that infrastructures which allows for used battery to be turned into the producers or certified recycling facilities are not currently in place. This would be necessary to prevent individuals from obtaining old batteries, tinkering with them, and causing a potential accident.

Even once the industry can come to an agreement on how to safely de-cycle used Li-ion batteries, the cells will still eventually degrade to the point of no longer being able to be used in an energy storage capacity. In that case, recycling the materials to make more batteries can be environmentally viable. One study shows that cathode production with recycled materials can decrease exergy consumption by more than 50%.

Recycling must occur more consistently in order to develop efficient processes and to perform an assessment on recycling of batteries from a life cycle perspective [50].

3.4.6.9 Forecast of the marine battery second life market

Figure 49 present at the left the estimation and forecast of the energy of first life batteries (WP1, sec 3.3.3).

Assuming that the battery life-time is approximately 10 years, and that the remaining capacity at the end of life is 70% of the nominal one (as suggested by the NREL study, Paragraph 3), the forecast of the total energy potentially available for second life applications, can be calculated by shifting 10 years ahead the second-life energy estimation. The forecast of the second life batteries energy is presented at the right of the Figure 49.

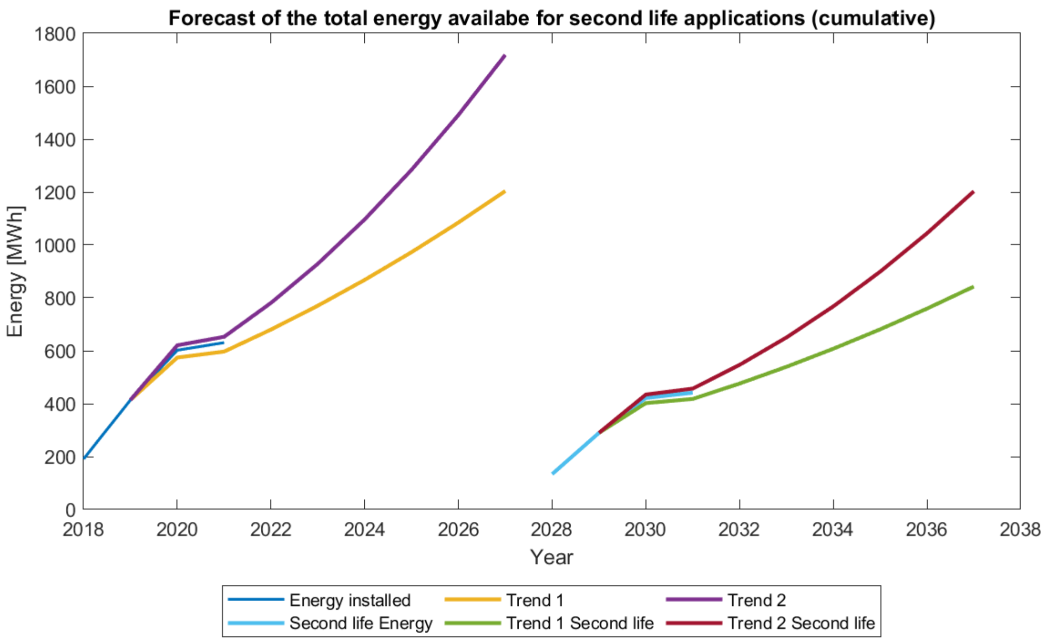


Figure 49 - Forecast of the total energy available for second life applications. (cumulative).

In Table 3 (sec 3.4.6.3) the costs of second life batteries available from the literature are presented. Figure 50 illustrates the potential market size, based on the forecast of the total energy available for second life application of marine batteries, considering 110 €/kWh as cost (average of the costs 132$/kWh reported in Table 3 converted in €).

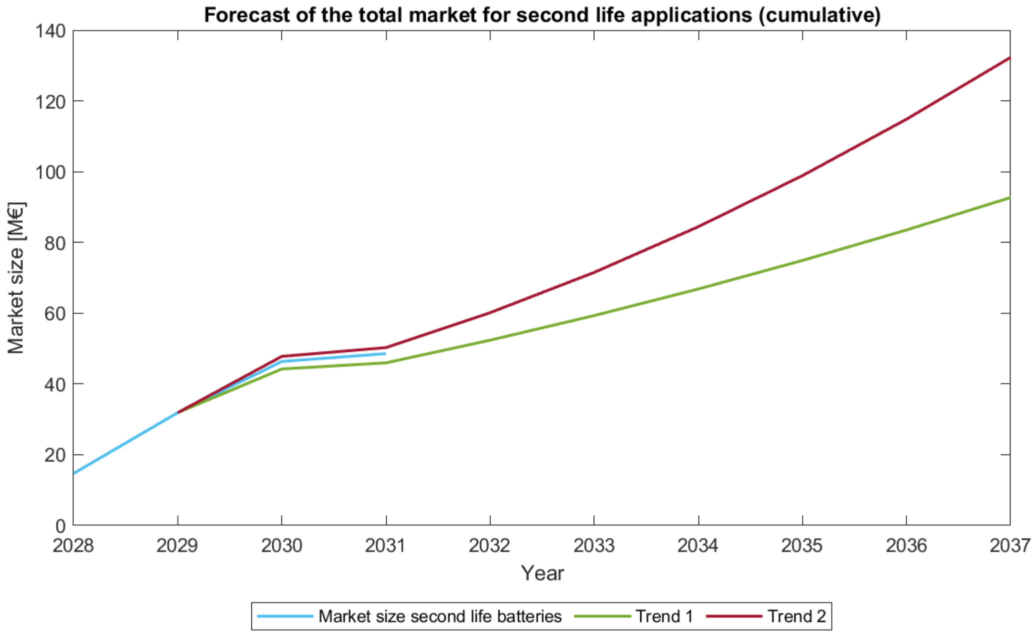


Figure 50 - Forecast of the total market of marine second life batteries (cumulative).

3.4.6.10 Recycling cycle

A complete consideration of the Recycling cycle and its processes is essential to showcase the ecological and economic benefits. This could boost the general interest in investing in Recycling. A hydrometallurgical process can help achieve a closed-loop economy, as shown in Figure 51. The feasibility and efficiency of this approach has been already demonstrated at pilot scale and under optimal conditions. Following efficiencies have been achieved [34] [31]:

- Copper: 100 %
- Manganese: 99,2 %
- Cobalt: 97,8 %
- Nickel: 99,1 %
- Lithium: 95,8 %

NCM precursor material and Lithium-hydroxide (Li-OH) are recovered efficiently and can then directly supplied into the CAM production process. A detailed description of the process can be found in [34].

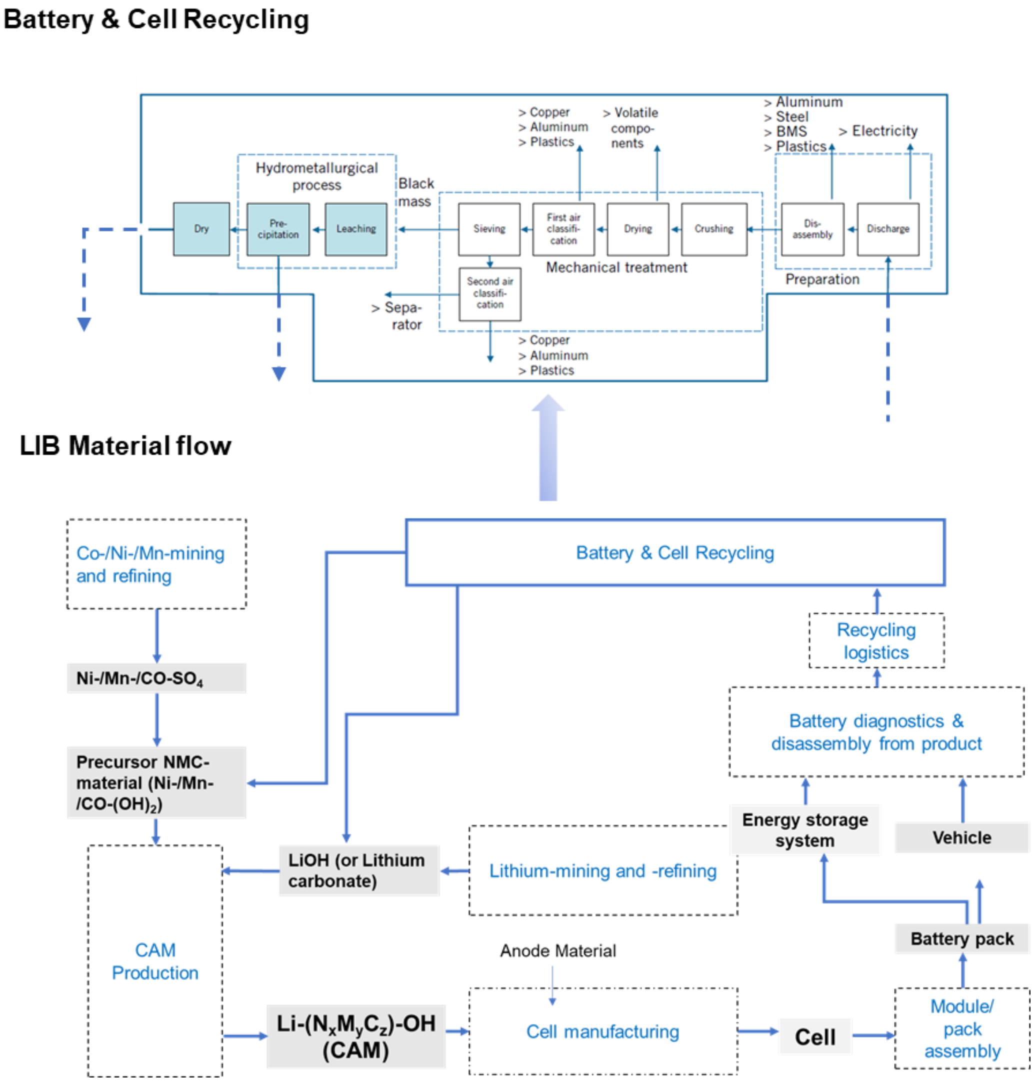


Figure 51: Battery & cell Recycling (hydrometallurgical process) and material flow in LIB [31]

3.4.6.11 Recycling processes and optimization

The optimization of the different processes of recycling have been lately a subject of different research activities in Europe.

The Project Re2Live [51] investigates the entire value chain of recycling of car batteries and stationary energy storage devices from different perspectives. The following four areas are considered:

- Logistics
- Automation and processes
- recycling
- Second-life applications

The main objective of the project is to keep materials and raw materials in the economy of the Flanders region in Belgium for as long as possible and to reduce waste generation to a minimum. For this purpose, the required research activities for the different steps of the value chain of battery recycling and the technical potential as well the economic feasibility must be investigated.

The Project ECO^{2}LIB [52] addresses the entire battery value chain using advanced characterization, modeling, and simulation methods. The following areas are investigated:

- Material selection and optimization
- Cell and battery production
- Use phase
- recycling phase: The main goal is to realize and investigate more eco-friendly approaches for LIBs with high recycling rate at lower costs.
- Sustainability of the full life cycle of battery: the environmental and economic aspects of the battery systems are analyzed.

The main objective of the project is to improve the materials of energy storage applications with significantly reduced costs per cycle. To reach this, following goals are pursued [52]:

- Cost reduction up to 85%
- Enhanced battery lifetime up to 20 years
- Improved recycling up to 58%

The recycling processes and the various interactions are shown by means of two example projects. Two pilot projects *LithoRec* (Recycling of Lithium-Ion Batteries) and *LithoRec 2* [53] strived to develop and improve the different processes and a full life cycle concept of recycling.

Both projects are funded by the Federal Ministry of Environment, Nature Conservation and Nuclear Safety in Germany and involve different partners of the automotive, chemical, recycling industry and various institutes.

Part of the *LithoRec-Project* [54] is to develop a holistic approach for recycling planning. For this purpose and considering the growth of battery market, following aspects are taken into account:

- Determination of optimal locations for battery dismantling, collection recycling facilities
- Determination of recycling capacities

The main goal of the project is to optimize the recycling of LIB accounting for environmental economic, legal, and technical aspects. For this purpose, a mathematical optimization model is developed that defines the sequence of the processes as well the number and capacities of the workstations. Based on the results of the study the recycling network is designed and the recycling facilities of exploiters are configured. The automation of disassembly was also theoretically investigated. Part of the project was to design a possible recycling plant capable of processing of 700 kg cell material from the individual steps. A process flow diagram was created for that purpose. The Individual plant components, machines and equipment were designed, and possible suppliers were determined.

The ecological evaluation of the *LithoRec* process within the scope of the life cycle assessment (LCA) in accordance with ISO 14040/14044 showed a positive ecological impact. The economic evaluation shows that the *LithoRec* recycling process in combination with mechanical processing could be operated economically starting from an annual volume of approx. 4,500 t systems or 15,000 BEV systems. The profitability of the individual processes can be considerably affected by certain factors. The main factor is the price for the recovered materials.

The aim of the *LithoRec II* project [53] [55] is both the further development of the processes developed in *LithoRec* as well as the development of further processes (e. g. for the recovery of liquid electrolyte). In parallel with the research work, a new pilot plant (Figure 52) has being realized that can process up to 100 tons of battery cells in such a way that the separated active materials can be recovered in high quality in the already existing pilot plant for hydrometallurgical processing. In particular, the interaction of the individual processes is considered. For this purpose, the material and energy flows of the process steps are determined. The process steps will be then analyzed and visualized using simulation. This will make it possible to derive initial proposals for optimizing the operation of the pilot plant in terms of production economics. Based on the findings, scenarios are developed regarding economics of the processes of the pilot plant, which allow a more in-depth economic analysis and optimization. The overall evaluation of the LCA results for the recycling of the NMC battery type with aluminum casing shows considerable positive impacts on the global warming potential (GWP).

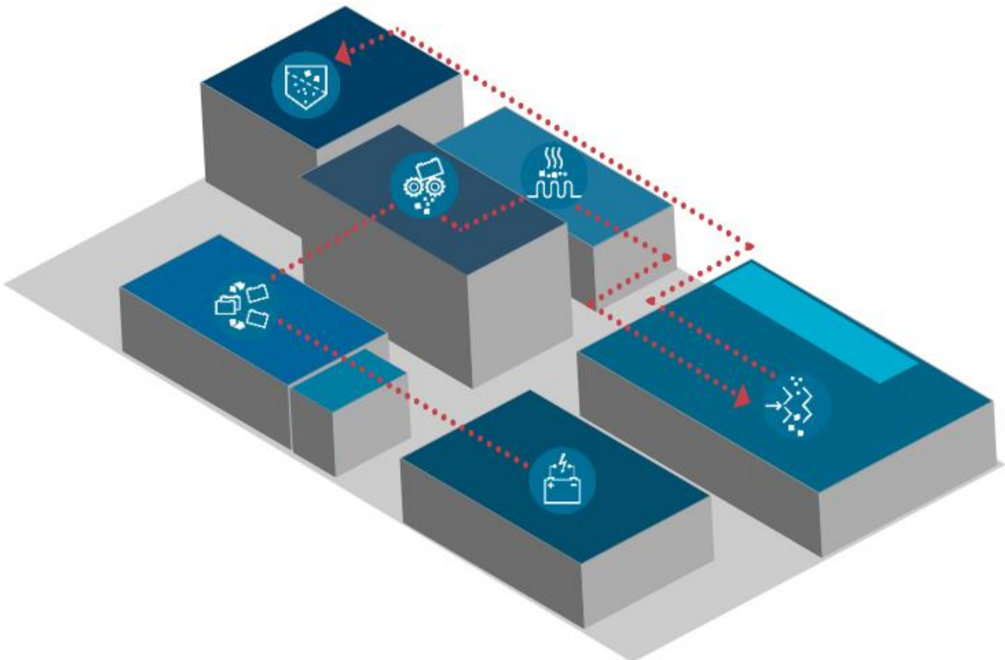


Figure 52: Recycling Pilot Plan of the LithoRec II project [55]

3.4.7 Recycling potential, Europe position and Regulations

This chapter discusses the potential of recycling, Europe's position, and the current legislative situation of recycling.

3.4.7.1 Recycling potential

The LIB recycling market annual growth is expected to be at 19.6% starting from 2020. The market was valued at $403.77 million in 2019 and is expected to reach $1.392 Billion by 2027. [56]

Assuming an 80% recycling rate after 10 years of usage and at the price levels of 2018 of the raw materials, Roland Berger conducted a study [31] to forecast the generated revenues of active material's recycling and the recycling volume in the future. The predictions are based on costs for mechanical treatment and hydrometallurgical processing. The battery recycling market value could reach 2,6 Billion euros by 2030 and 17,6 Billion euros by 2040.

Assuming a volume of 1,8 Million tons of recycled battery packs in 2030 (6 million tons in 2040), an amount of 250.000 tons of active materials (nickel, cobalt, manganese, lithium) could be recovered by 2030 (850.000 tons in 2040). This represents more than 20 % and of the LIB demand and will generate revenues between 3 and 6 Billion Euros in 2030 (20 to 40 Billion euros in 2040). [31]

3.4.7.2 Europe Position

In 2019 the LIB recycling capacity amounts to approximately 100.000 tons globally.

With more than two thirds of market share, China is the world leader in Recycling of battery cells, as shown in Figure 53 (Status 2018). This is mainly due to the large Chinese market and the state's regulations. Recycling facilities must, inter alia, set up by OEMs of electric vehicles [31]

Production stage	Battery cell	Cathode material (CAM)	Cobalt refining[1]	Cobalt mining[2]	Lithium refining	Lithium mining	Anode material (AAM)	Graphite refining	Graphite mining	Recycling battery cells
CHINA	~67%	~70%	~62%	~1%	~51%	~13%	~75%	>99%	~56%	~68%
EUROPE	<7%	0%	<18%	<1%	0%	0%	0%	0%	0%	<5%

Figure 53: Lithium-Ion value chain shares in 2018: comparison between Europe and China [37]

With the increase in investment in battery's factories in different European countries, the battery recycling industry in Europe could benefit from the growing market. To be able to compete with China in the future, different measures are necessary [31] [37]:

- Regulation and clear political framework on the EU level
- Promotion of beyond the state-of-the art research of active material recovery
- Digitalization of the recycling processes to advance the level of automation in disassembling of batteries (e.g. Machine-readable information with details about the cell chemistry) and install a track and trace mechanism of used batteries.

Europe export of used batteries, which are recycled in other countries, is a major obstacle of the development of battery recycling in Europe. Export restrictions could offer a planning security for European companies to build up the necessary capacities. [37]

3.4.7.3 Regulations

Regulatory requirements for battery recycling provide the basic framework for the further development. One of the challenges in recycling is the immature regulatory regime. Most markets today have regulations regarding recycling of consumer electronics. Specific requirements for EV-batteries are lacking. A specification of responsibility between the producer and consumer and objectives for recycling rates are still missing.

Different regulations in Europe exist for battery vehicles and provide a legal framework:

- Directive 2006/66/EC [57]:
  This directive applies to all types of batteries and accumulators and defines the recycling, collection, and disposal procedures.
- Directive 2000/53/EC [58]:
  This directive is related to the recycling of end-of-life vehicles. The recycling of batteries (as used parts) should be integrated in the design and production of new vehicles.

In addition to the EU, automotive batteries in Japan are subject to the "Automobile Recycling law". Other countries like China and South Korea have also taken measures to manage the utilization and recycling of batteries. [31]

A new battery regulation was proposed by the EU commission on the 10th of December 2020. [59] The regulation is intended to ensure the safety and sustainability for the batteries placed in the EU as response to the growing battery market in Europe. Part of the regulation insures that the battery dismantling information is accessible for the remanufacturers, second-life operators and recyclers.
An updated overview about the legalization of waste and recycling of batteries and accumulators can be found on the website of the EU commission [59].

The absence of laws regulating whether batteries should be reused or recycled, creates uncertainties for battery manufacturers and leads to regional differences concerning the end-of-life management of used battery packs.

3.4.8 Outlook

Battery Recycling in the future will depend mainly on the following aspects:

- Market growth of the electric and hybrid vehicles and the related battery pack prices:
- Development of the availability and price of critical raw materials
- Policy of the different countries regarding Recycling and reuse of LIBs
- Efficiency automation of the different recycling processes and recycling's economics.
- Optimization and planning of the full recycling process

Further development of the battery recycling requires not only economic and technical consideration but also the implementation of legal conditions to optimize the recycling process and provide a competitive investment environment with Asia.

3.5 LCA

3.5.1 Introduction

The main objective of this Deliverable is to analyse the benefit or cons in relation to the adoption of lithium batteries on board ship. Two case studies were defined, the first one is a small ferry carrying cars and passenger on a 2 hours round trip 6 trip every day in north Europe. The second case is relevant to a large ferry operating in a two full days round trip (20 hours navigation and 4 hour stop in each of the two ports. The analysis is based on a simplified Life Cycle cost and life cycle analysis, comparing traditional solutions with those equipped with batteries and calculating various environmental and economical KPI.

.This document has been divided as follows.

Therefore, the activity performed was aimed to:

- Identify two significant case studies
- Identify for each case study possible operative scenarios,
- Perform a simplified LCA and LCC analysis based on selected scenario comparing innovative solutions to conventional ship, used as baseline.
- Calculate the cost and environmental KPI on a life cycle base

Calculation were performed using LCPA tool by BALANCE [60] , This software, developed in European projects JOULES and successively implemented in various Research Project allows to compare the economic and viability of different investment options. Moreover, it is possible to analyse the environmental footprint with reasonable effort by focusing on the main impact categories: Global warming potential, Cumulative energy demand, Aerosol formation potential, Eutrophication potential, Acidification potential.

Figure 54 Life cycle of a ship

3.5.2 Ship data

Two different size of ships were selected for the analysis, a medium /small ferry operating in North Sea and a large cruise RO-PAX operating in the Mediterranean. Herebelow a short description and main characteristics of the two vessels.

3.5.2.1 Small ferry

This case is based on medium sized ferry for passengers and cars, trucks and cargo relevant to island communities, coastal zones and inland waterways. Baseline is propelled by a diesel electric generator while the innovative ship is equipped with lithium battery pack which allows a full electric zero emission operation. Ship dimension and power are the same for the two ships type. In Table 6 main characteristics of the two ships are reported.

Ship type	**Small/Medium ferry**
Deadweight - DWT [t]	187
Lightweight - LWT [t]	746
Operational Speed [kn]	13,5
Lenght btween perpendiculars - Lbp [m]	57
Breadth - B [m]	12,8
Draft - T [m]	3,7
Gross Tonnage - GT [tons]	996
Total passenger	196
Total lane meters	145 mt
Main engine power	2x700 kW
Crew	4

Table 4 Small Medium ferry main data

3.5.2.2 Large ferry

This case is addressed to a large cruise ro-pax operating on Mediterranean routes. Also in this case the main dimension, capacity and speed of the baseline and innovative vessel are the same. Main difference is related to the presence on board of a 5500 kWh battery pack capable to operate at zero emission during last mile from port.

Ship type	**RO-PAX**

Operational Speed [kn]	23,5
Lenght [m]	254
Breadth - B [m]	30,4
Draft - T [m]	7
Gross Tonnage - GT [tons]	63742
Total passenger	3500
Total lane meters	3050 mt
Main engine power	55.440 kW

Table 5 Large ferry main data

3.5.3 Operating profile

3.5.3.1 Small ferry

Small ferry operate on a 6 round trip a day linking two cities at 1 hour navigation distance.

The ship is operating during daytime while overnight she remains moored at main port.

Every trip the ferry remain moored at port abt 20/30 minutes during this time batteries are partially recharged using a recharge station of 1200 kW power.

In order to simplify calculation the mission profile was summarized on a yearly base, considering:

- Building phase duration 1 year
- Operational life duration 25 years
  - Navigation 212 days per Year
  - Port stays during daytime 47 days per year
  - Port stays overnight 106 days per year
- Scrapping duration one year

In the model a main refurbishment of the ship at mid life is also included. During this phase batteries will be changed in the innovative vessel.

Figure 55 Small ferry life cycle phases

3.5.3.2 Large Ro-PAX

For large RO-Pax it was selected a conventional round trip between Italy and Spain ports. The mission profile consider three round trip every week, each one with 38 navigation hours, 8 hours moored in ports (4+4) and 2 (1+1) hours manoeuvring and mooring operation.

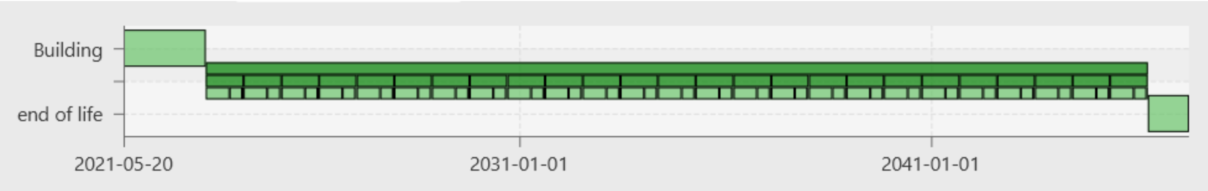


Figure 56 large ship life cycle phases

Two different scenario were taken into account for calculation. In the first one energy from batteries is used for thruster and hotel load during last navigation mile to and from port. Once the ship is moored, batteries are recharged using port electrical grid (average cost and emission calculated on average EU mix)

An alternative scenario considers that the ship when moored is completely zero emission and shore power connection (or cold ironing) provide energy both for battery recharging and for hotel load.

3.5.4 Results

3.5.4.1 Simulation Results for full electric small ferry

The calculation was made comparing a traditional diesel electric ferry using Marine Diesel Oil as primary energy converter to a full electric ferry which primary energy converter is given by lithium batteries. The differences in the two full electric scenario are substantially derived by the onshore electric power to recharge the battery when the ship is moored. In the first case price and emission are relevant to an EU mix while in the second case are relevant to completely green energy from renewal. This change in large way Global Warming Potential and Cumulative Energy Demand as we can see in the radar chart shown in Figure 57

As we can see in Figure 58 all KPI of the two innovative solution presents benefits respect to baseline. Only CED (cumulative Energy Demand) when the grid is a mixed between energy from fossil fuel and renewable is slightly more than baseline. This is due to energy production and transportation costs and losses.

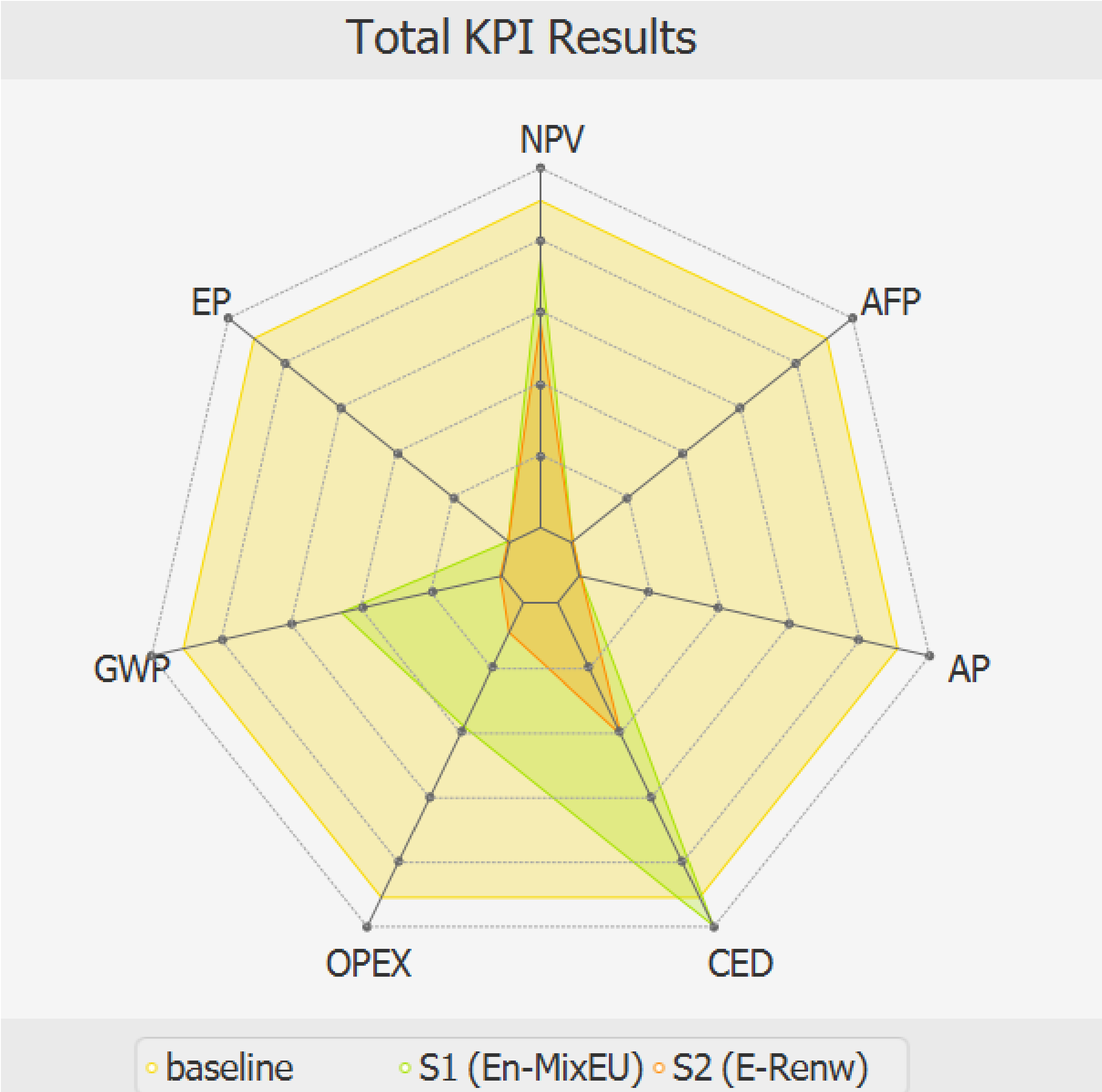


Figure 57 Small/medium size ferry radar chart

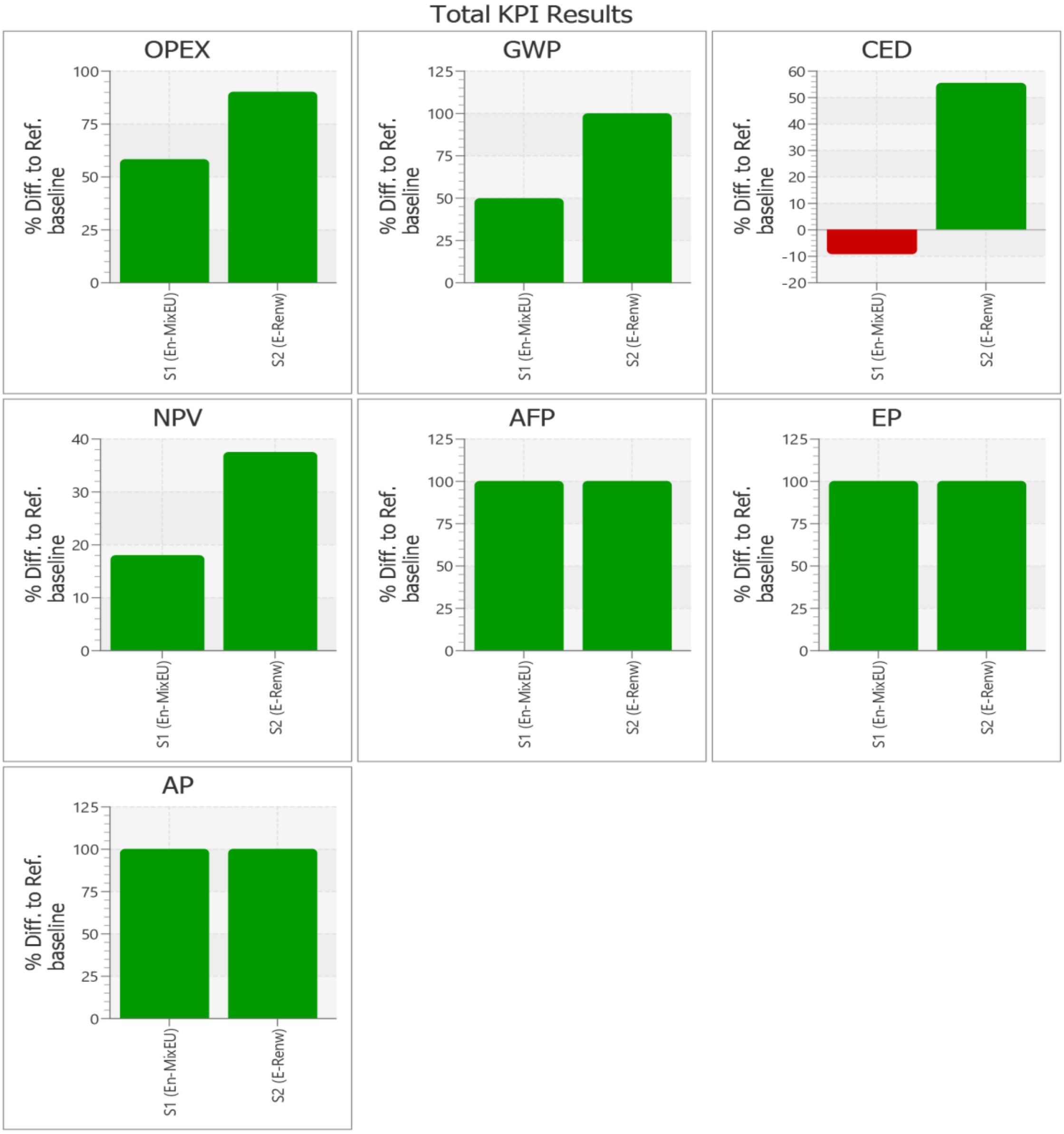


Figure 58 advantage / disadvantage respect to baseline

3.5.4.1.1 Global Warming Potential

The global warming potential represents the CO_2 and CH_4 in the emission.

In small ferry, as shown in Figure 59, CO2 is zero in operation phase in both innovative scenario. When the energy for grid to recharge batteries is obtained completed by renewables, CO2 and CH are substantially zeroed.

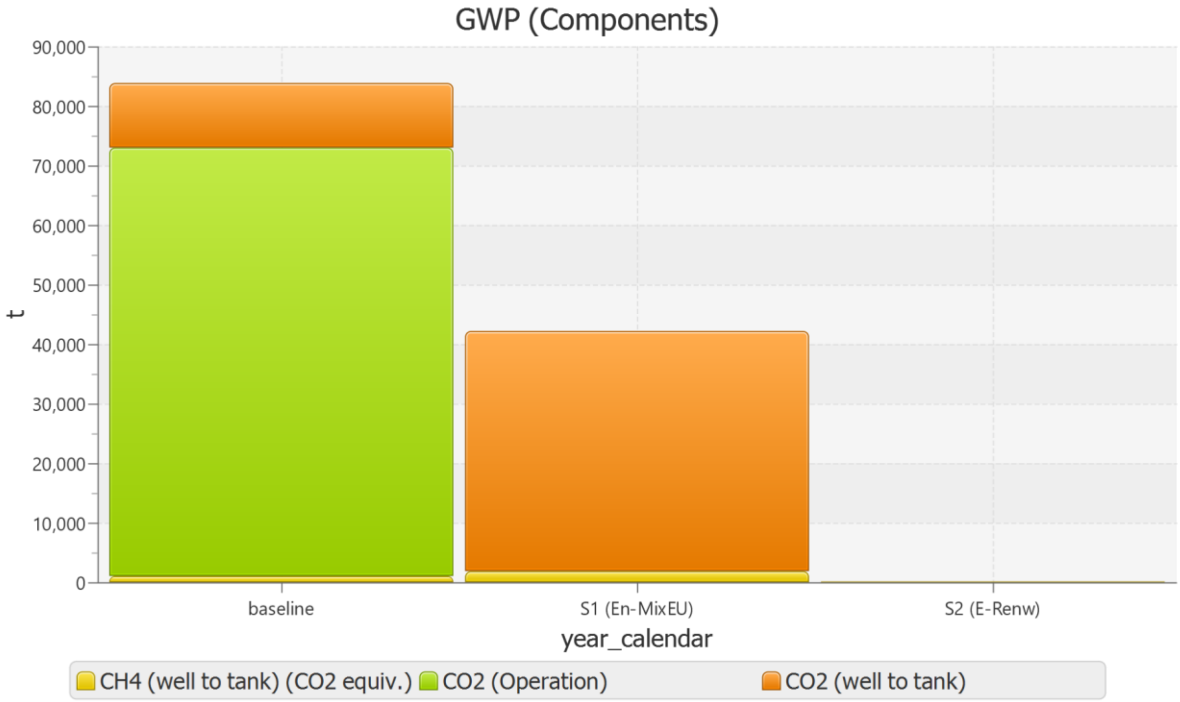


Figure 59 Small Ferry GWP

3.5.4.1.2 Cumulative energy demand (CED)

The cumulative energy demand is representing the direct and indirect energy needed during the process of creating the raw material, production process, and operation.

In this case the energy from terrestrial grid not renewable as a energy request higher than the traditional diesel electric ferry. This disadvantage can be solve using an energy grid for battery charging at port totally from renewable

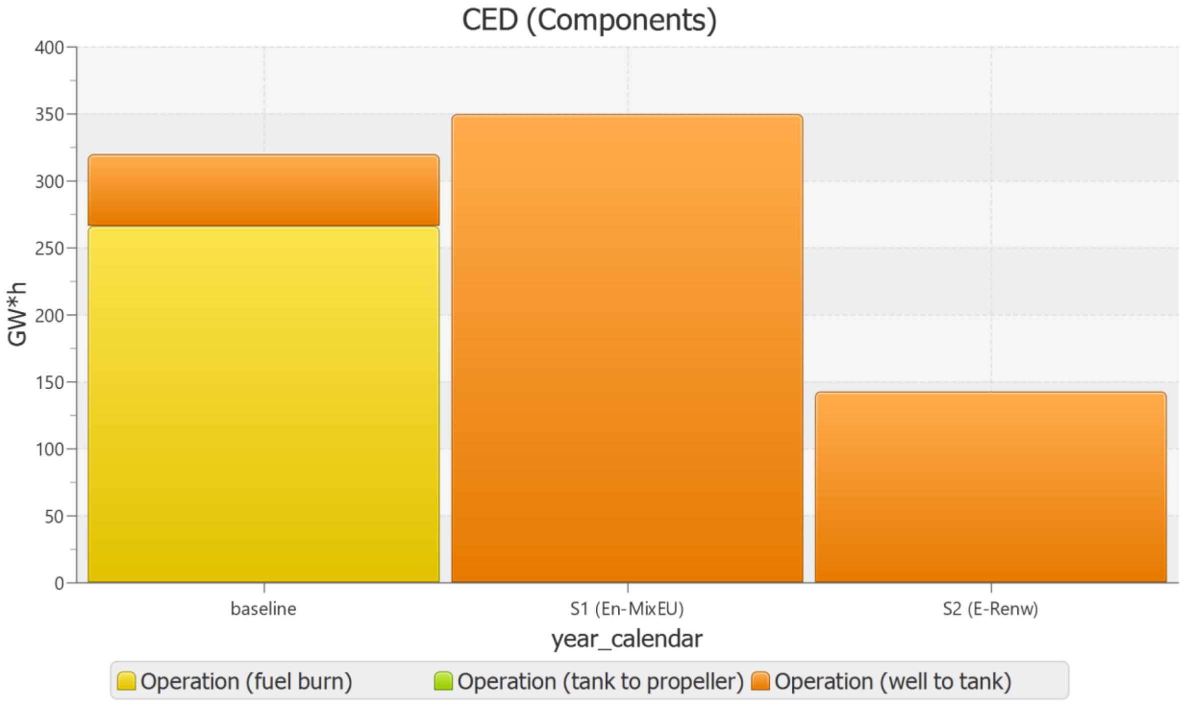


Figure 60 Small Ferry CED

3.5.4.1.3 Aerosol formation potential

The Aerosol Formation Potential (AFP) is the KPI that represents the small black carbon particulates, which are harmful for human health upon inhalation.

It is evident as the fully batteries equipped ferries having no combustion on board has a zero emission particulate

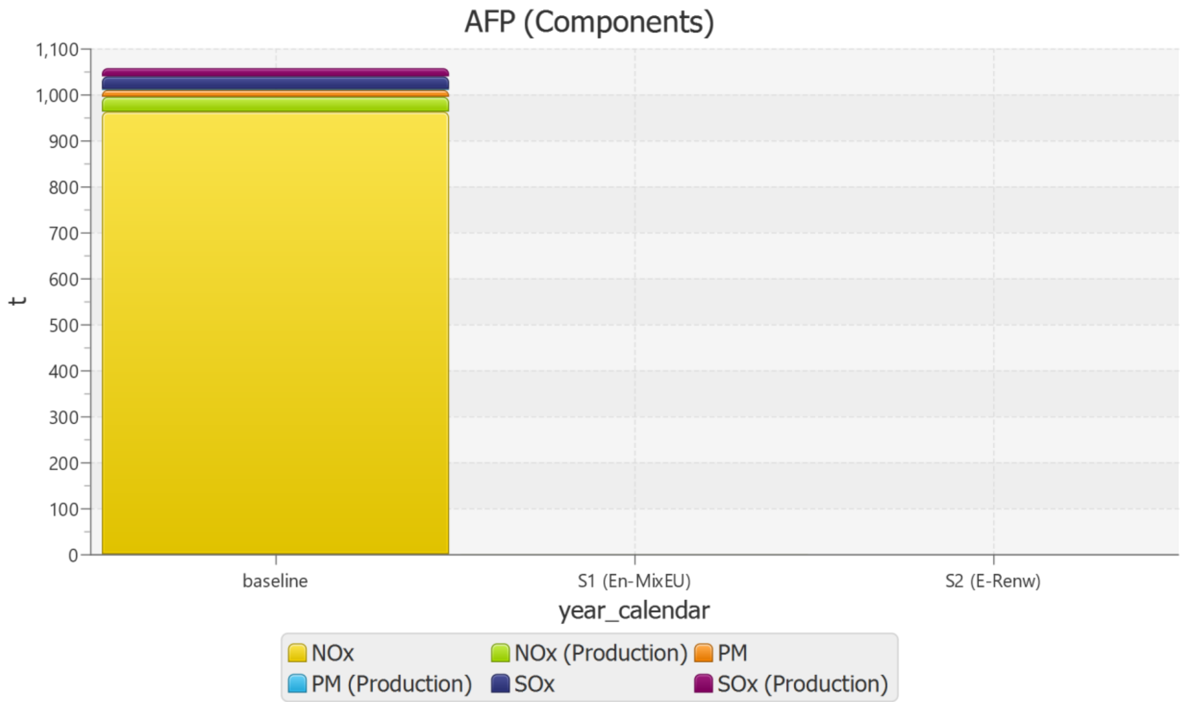


Figure 61 Small Ferry AFP

3.5.4.1.4 Acidification potential

The Acidification Potential (AP) KPI represents the part of impact from NOx and Sox on climate anomalies like Summer Smog, Acid Rain, etc.

It can be said as operational part has a prevalent impact on this KPI as the Internal combustion engine is responsible for the 99% of NOx and SOx emission during navigation and for hotel load during port stays.

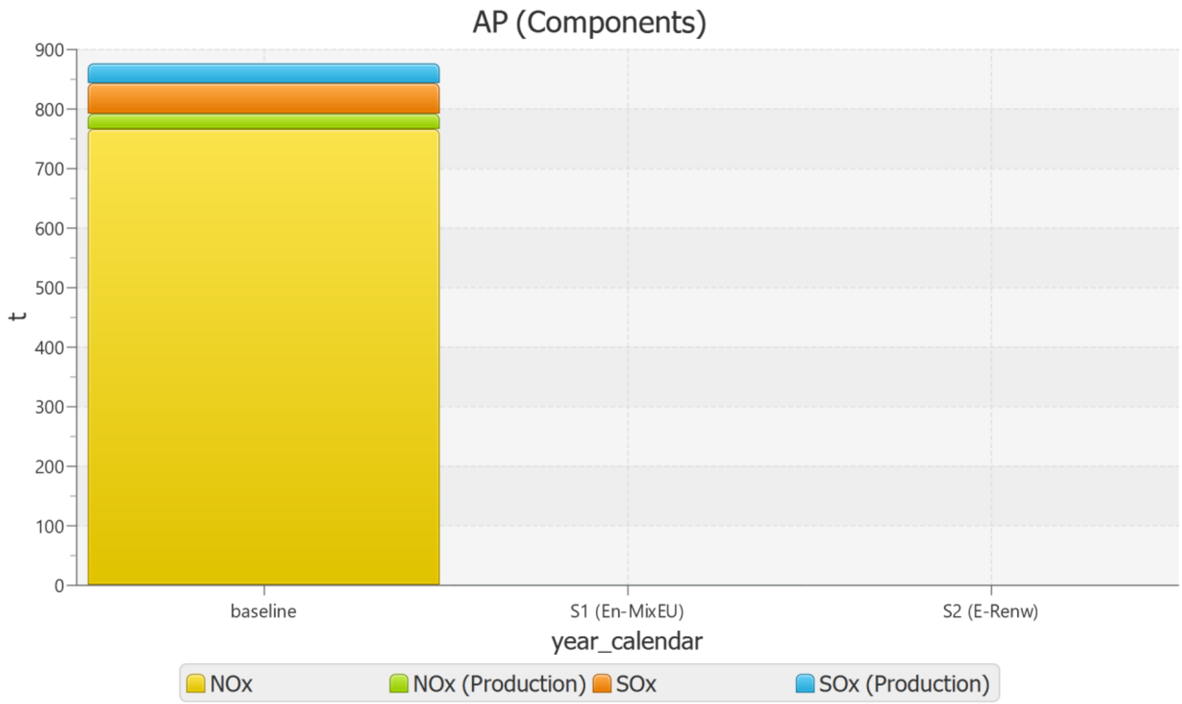


Figure 62 Small Ferry AP

3.5.4.1.5 Eutrophication potential

The Eutrophication Potential (EP) is representing the over nutrients of water and soil which causes the imbalance in the ecosystems.

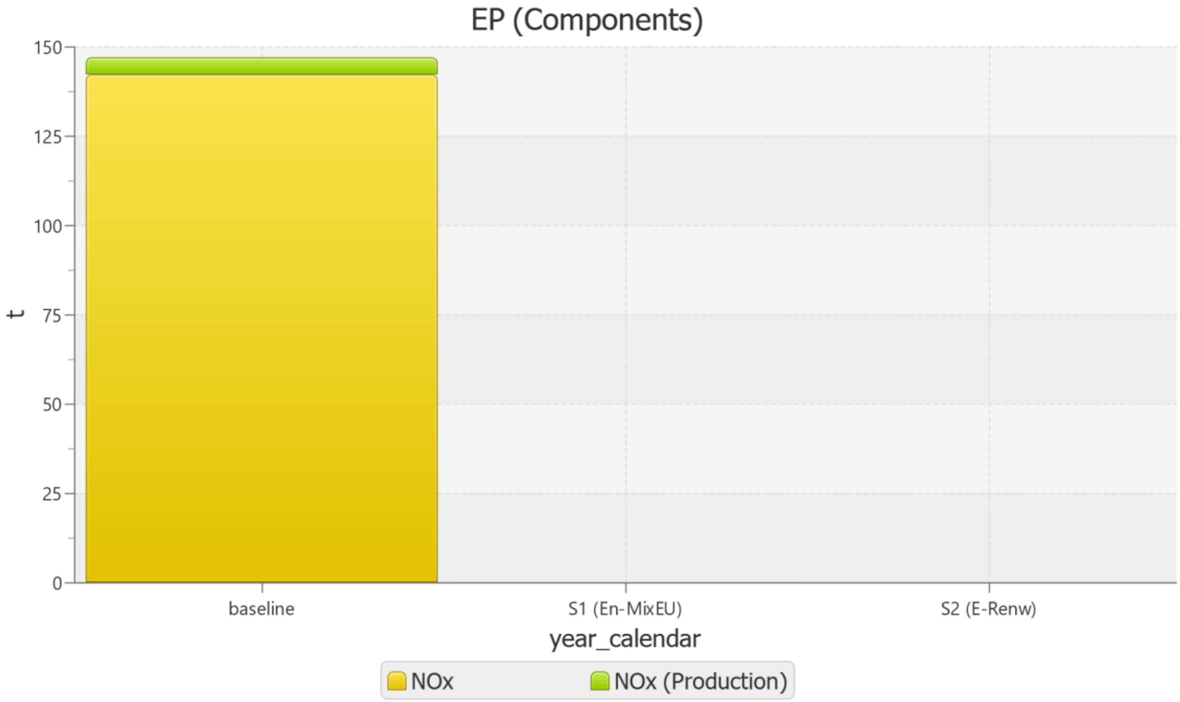


Figure 63 Small Ferry EP

3.5.4.2 Economic assessment

3.5.4.2.1 Net present value (NPV)

The net present value analysis takes into account the production cost, operating cost, end of life value, for 25 years of ship operation. The NPV is discounted with a rate of 10%. IN this calculation are not considered revenue as this has no impact on the different solutions.

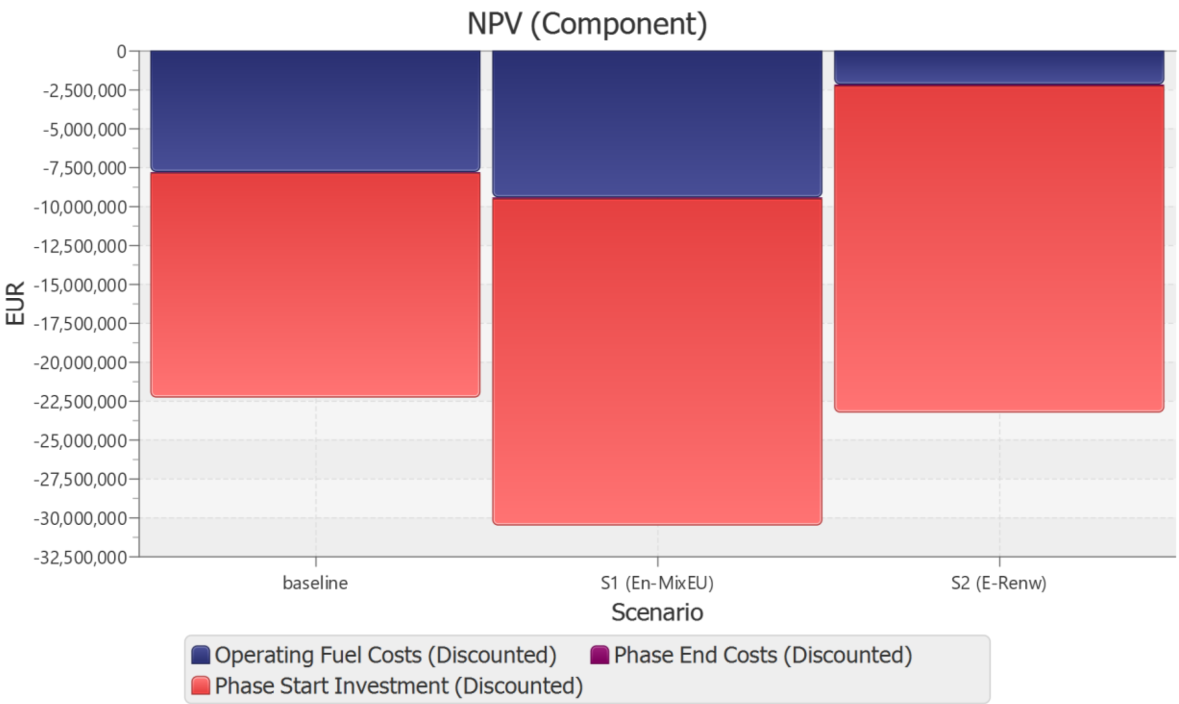


Figure 64 Small Ferry NPV

	Environmental assessment					Economic assessment
	GWP in t	CED in GWh	AFP in t	AP in t	EP in t	NPV [mill. EURO]
Baseline	83.857,19	319,59	1.057,07	875,72	146,98	-37.214.684,09
Small Ferry only battery Energy mix	42.204,61	349,53	0,21	0,24	0,02	-30.528.740,01
Small Ferry only battery Renewable	126,86	142,5	0,01	0,01	0	-23.271.004,03

Table 6 small ferry comparison table

3.5.4.3 Simulation Results Large RoPax with batteries for port operations

Baseline is a Large ferry propelled by conventional propulsion engine (HFO + Scrubber) during navigation and manoeuvring phase. Hotel load energy is generated by Auxiliary diesel generator in navigation, manoeuvring and when moored in port. Simulation was based on three different alternative scanrios named S1, S2 and S3. All these configurations have on board a lithium battery pack of 5500 kWh capacity.

During navigation phase batteries are used for peak shaving, allowing a reduction of fuel consumption of 5% in respect to conventional ferry due to optimisation of propeller engines regime.

In Scenario 1 Energy from batteries is used in port stays for hotel load. This scenario is addressed to port in which Cold ironing is not present. In this case batteries need to arrive at pier at full charge, therefore during manoeuvering and last mile to port energy is given by auxiliary MDO engines. Once the ship is moored batteries guarantee a total zero emission operation.

In scenario 2 and 3 Cold Ironing in port is considered available, thus it is not necessary to use batteries in this phase for hotel load. During mooring time batteries recharging energy and hotel load are provided by shore connection. The only difference between scenario 2 and 3 is the type of shore connection. In S2 is based on a mix of energy source (average EU Mix) while in S3 a completely renwable source energy is used.

In radar chart Figure 65 the differences respect to conventional ship are not so evident as the large part of operational life is navigation and fuel burnt has a huge impact on environmental and economical KPI

To have a better view of advantage in use of batteries is more appropriate Figure 66 in which the percentage respect to baseline (the ship without any battery on board) are shown for each KPI.

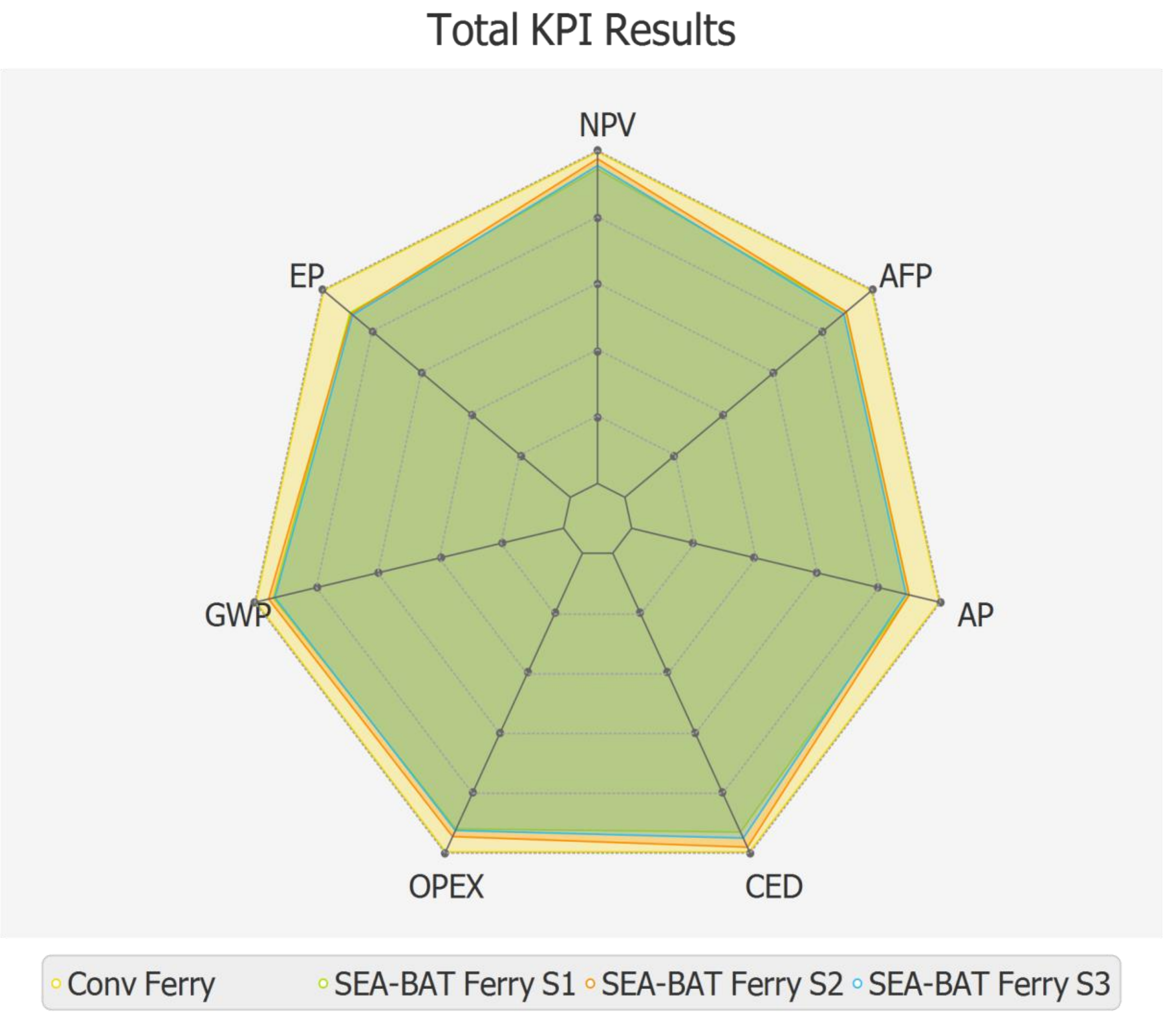


Figure 65 Large ferry radar chart

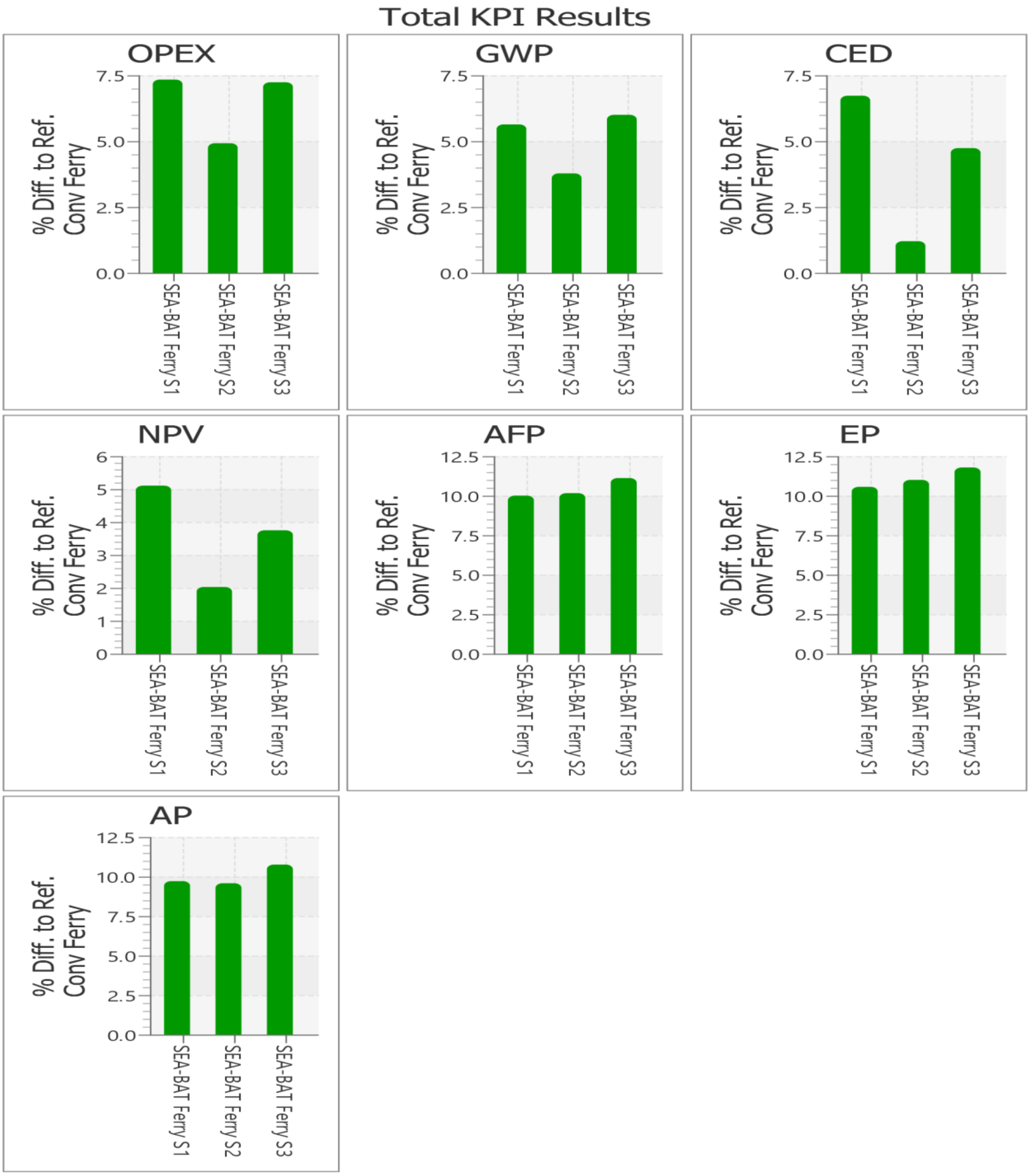


Figure 66 Large ferry advantage /disadvantage respect to baseline

3.5.4.3.1 Global Warming Potential

The global warming potential represents the CO_2 and CH_4 in the emission. Figure 67 shows how the major benefit in environmental terms are given by operating phase.

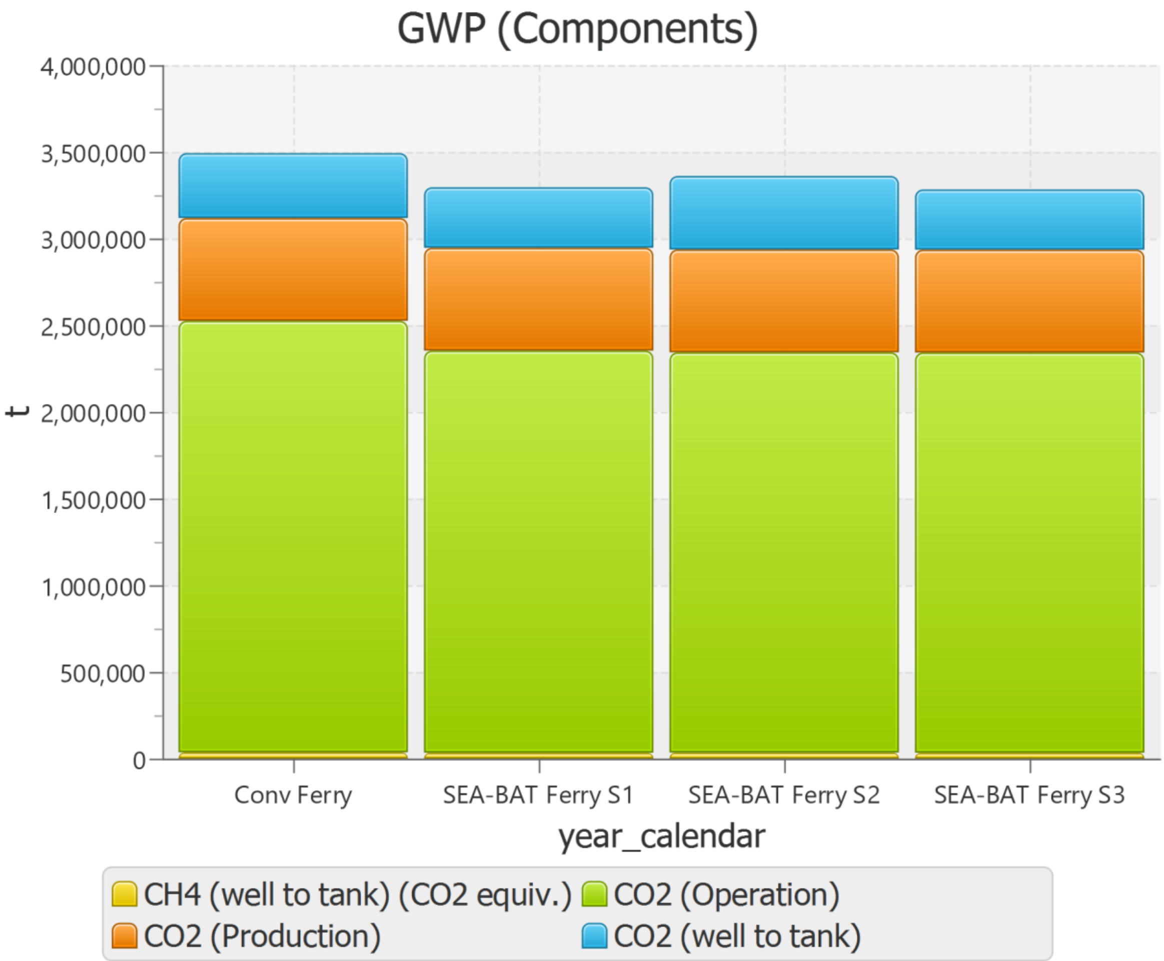


Figure 67 Large Ferry GWP

3.5.4.3.2 Cumulative energy demand (CED)

The cumulative energy demand is representing the direct and indirect energy needed during the process of creating the raw material, production process, and operation.

Due to Cold Ironing presence in V2 Cumulative Energy demand is higher respect to baseline and V1, This is due to energy cost for production and transport of electrical grid respect to well to tank energy of fossil fuel (Marine Diesel Oil)

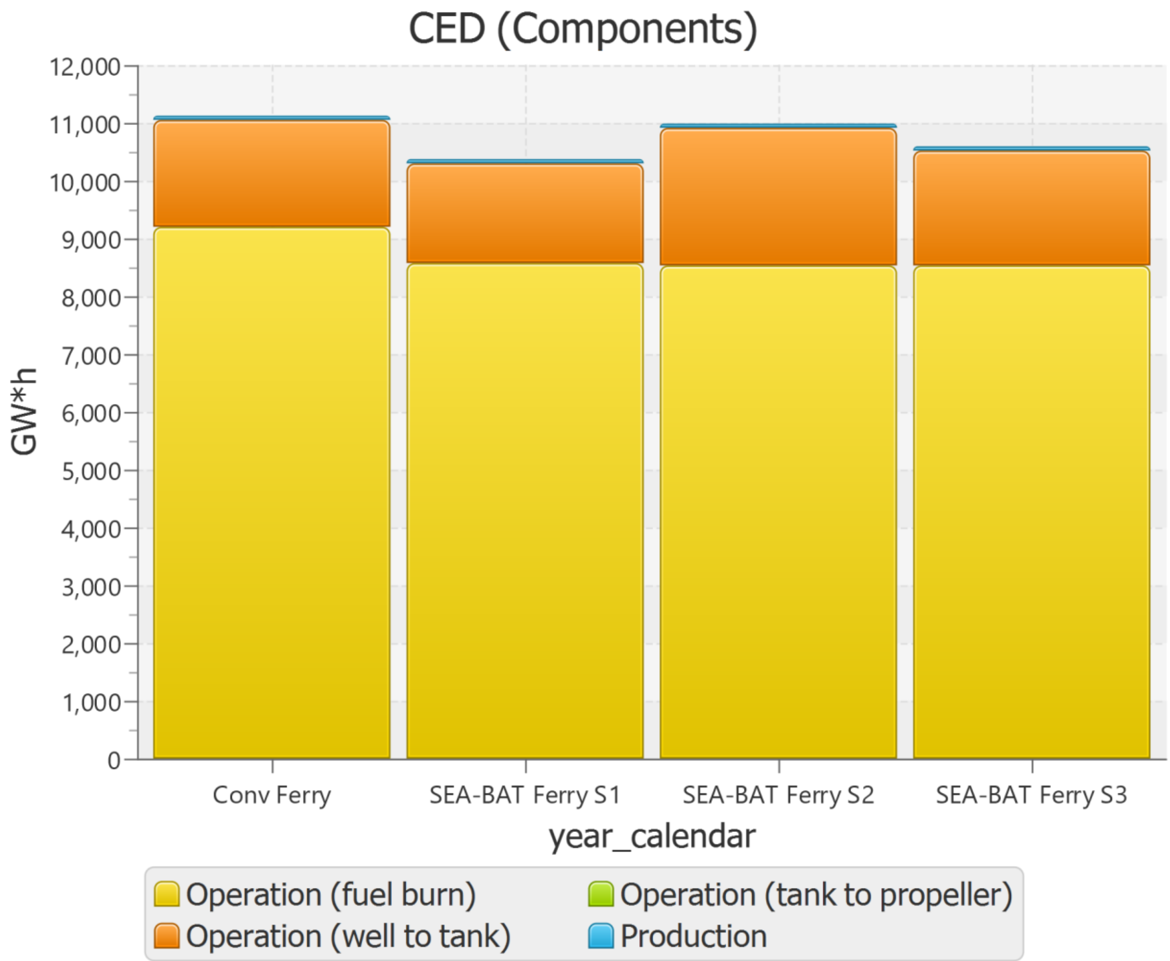


Figure 68 Large Ferry CED

3.5.4.3.3 Aerosol formation potential

The Aerosol Formation Potential (AFP) is the KPI that represents the small black carbon particulates which are harmful for human health upon inhalation.

The Last mile and port operation using batteries has a significant effect, particular importance because this reduction is obtained in large cities and port area.

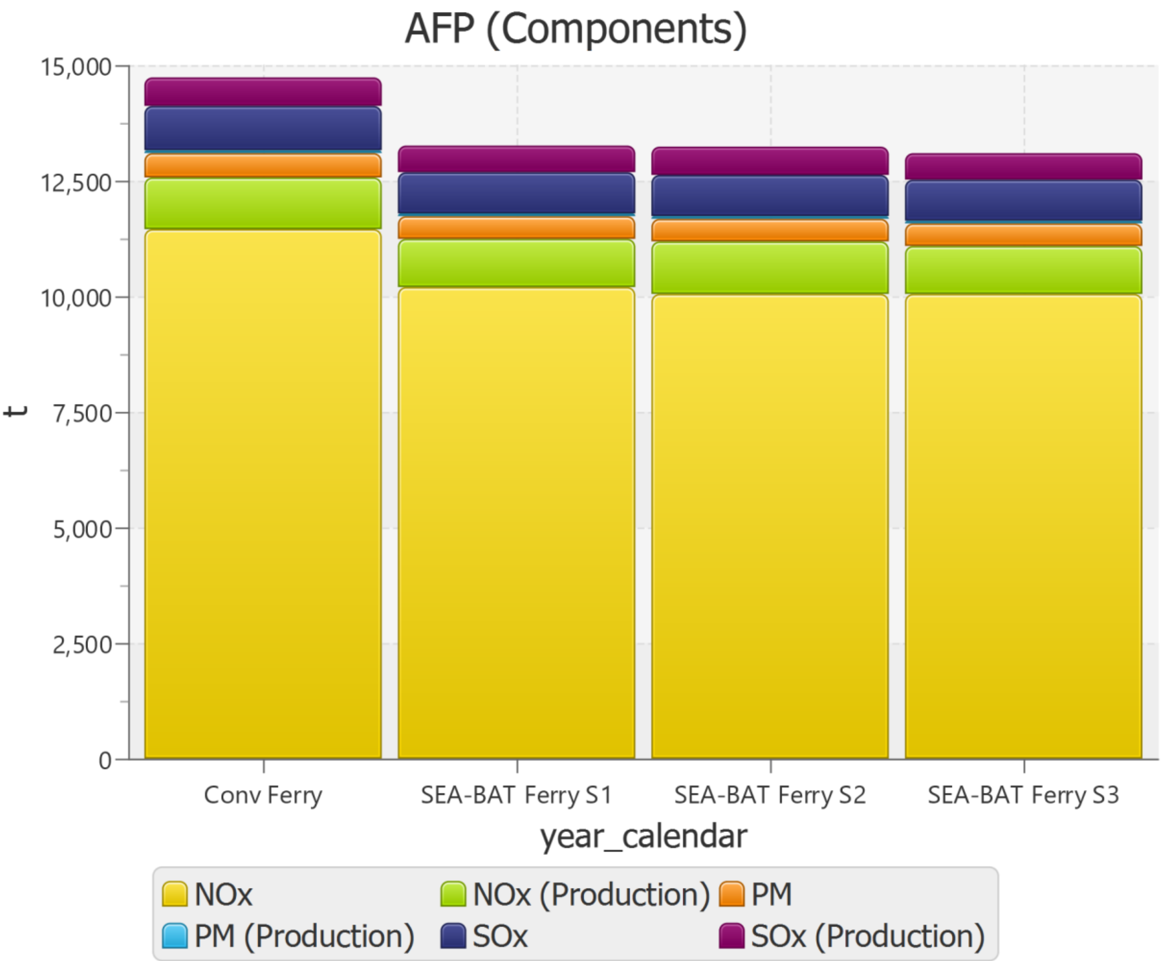


Figure 69 Large Ferry AFP

3.5.4.3.4 Acidification potential

The Acidification Potential (AP) KPI represents the part of impact from NOx and Sox on climate anomalies like Summer Smog, Acid Rain, etc.

Also in this case the reduction is due to battery use during port operation.

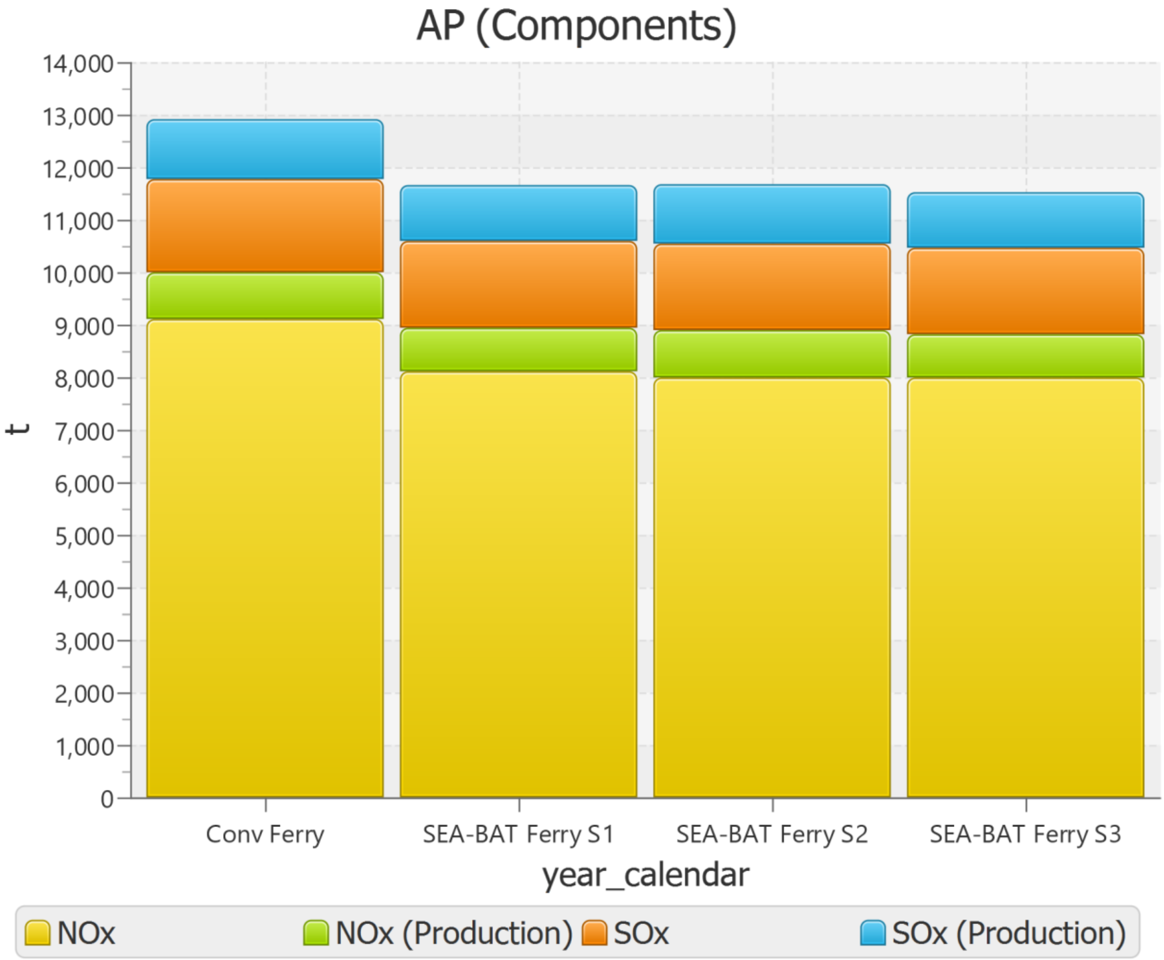


Figure 70 Large Ferry AP

3.5.4.3.5 Eutrophication potential

The Eutrophication Potential (EP) is representing the over nutrients of water and soil which causes the imbalance in the ecosystems.

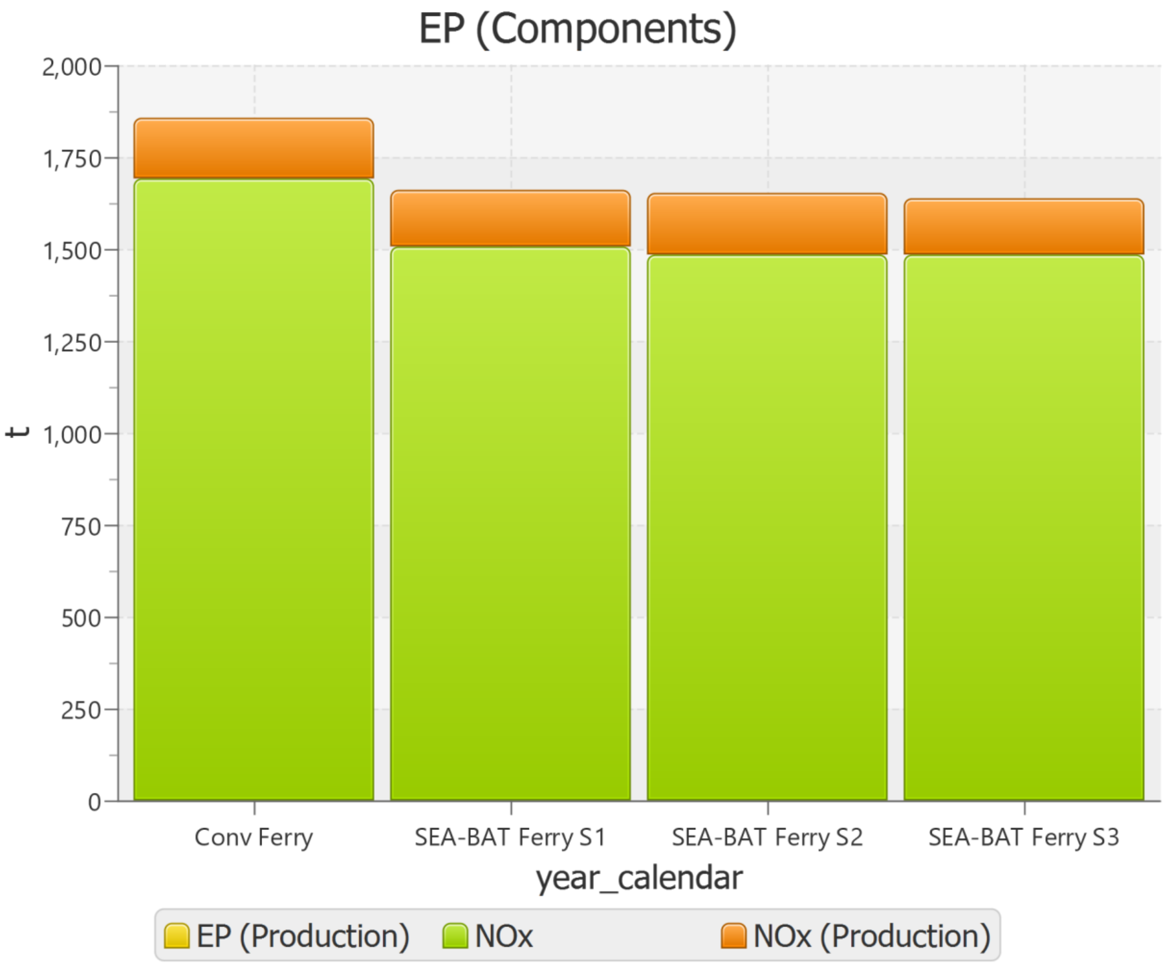


Figure 71 Large Ferry EP

3.5.4.4 Economic assessment

3.5.4.4.1 Net present value (NPV)

The net present value analysis takes into account the production cost, operating cost, end of life value, and operating revenue for 25 years of ship operation. The NPV is discounted with a rate of 10%..

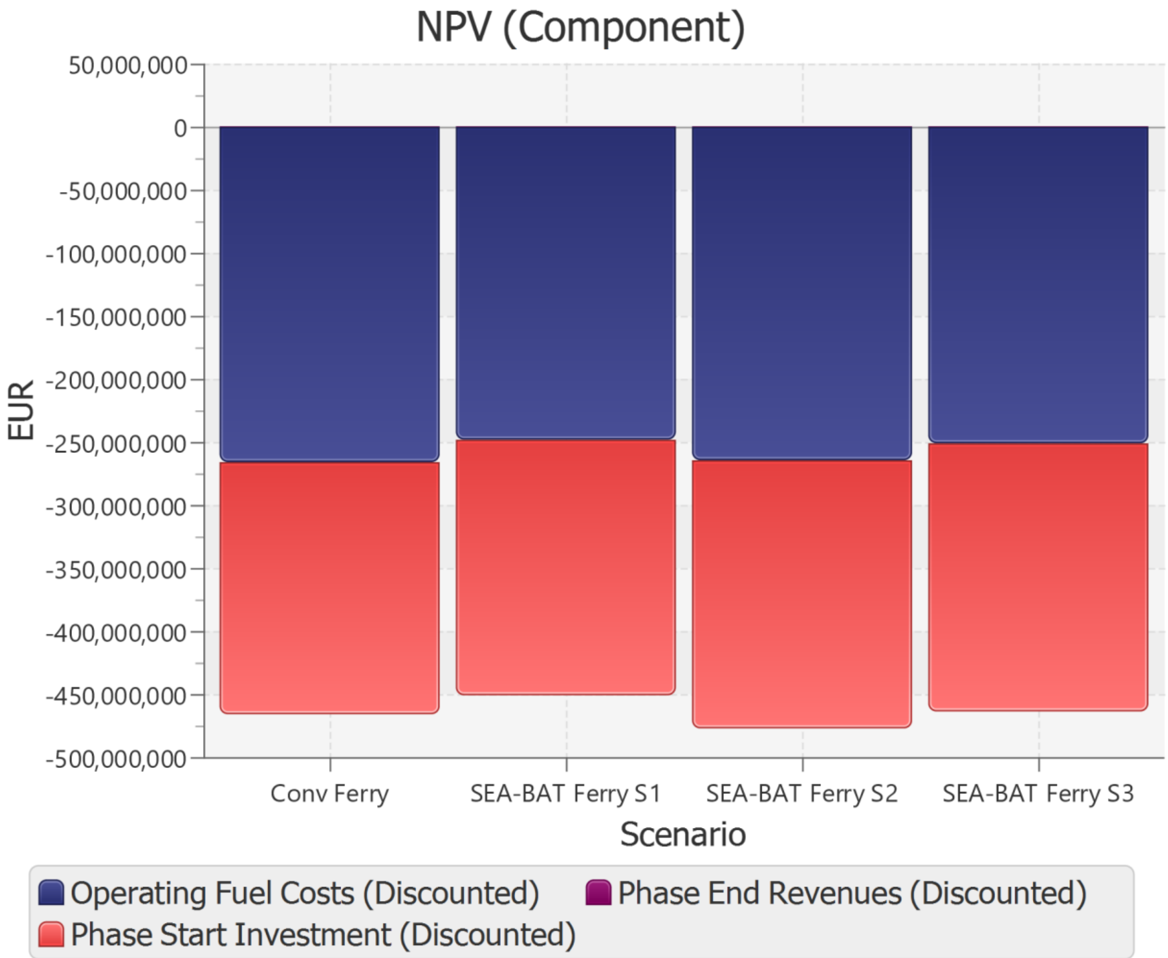


Figure 72 Lareg Ferry NPV

	Environmental assessment					Economic assessment
	GWP in t	CED in GWh	AFP in t	AP in t	EP in t	NPV [mill. EURO]
Baseline	3.493.131,51	11.126,03	14.736,08	12.916,63	1.857	-780.642.358,51
Large Ferry (S1)	3.296.162,1	10.377,49	13.260,78	11.661,55	1.661	-740.766.627,11
Large Ferry (S2)	3.361.089,0	10.991,98	13.237,84	11.678,61	1.652	-764.802.333,57
Large Ferry (S3)	3.283.416,6	10596,95	13.097.095,9	11.595,9	1638	-751,358,121,9

Table 7 Large Ferry Comparison table

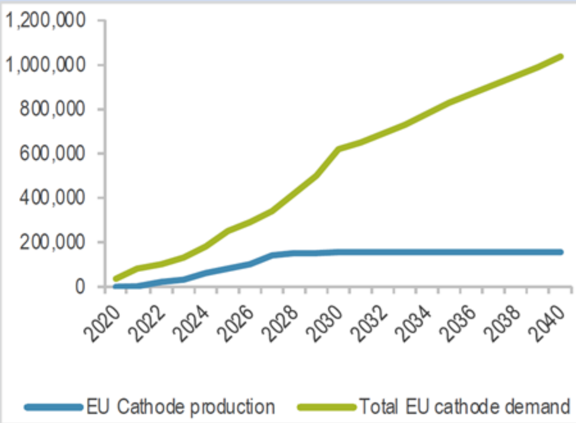
3.5.5 Outlook

In both the scenario analysed batteries have a positive impact on environmental aspects. This impact is absolutely considerable in case of small ferry completely operated by batteries as emission in operating place is completely reduced to zero. In case of use of renewable energy for battery charging a real zero emission transport can be obtained. In large ferry, the major source of emission are due to fuel burn during operation for propulsion. The advantage from batteries is negligible in absolute terms but it is obtained in port and during last mile operation. Commonly ferry port are inside city centre so obtaining a considerable reduction of emission in these area certainly worth the investment.

4 Discussion, Conclusions and Recommendations

4.1 Conclusions

In the following table a schematic representation of the main outcome regarding the various issues faced in this document are reported

Item	Main conclusions
An analysis of lithium-ion batteries material providers and investment plans	Since the Lithium-ion technology development is primarily driven by consumer electronics and automotive market, materials and battery providers have not developed strategy related to the maritime industry. The current projects in the maritime industry focus on evaluating the available technology and how to integrate it into a maritime environment the three Asian countries (China, South Korea and Japan) dominates the supply of Li-ion cell components. To satisfy the increasing demand recycling is one of the most important lever for EU countries. the recovery of raw materials from recycling would make it possible to bridge the gap shown in the picture below.  Different European players are targeting to close the loop and to establish themselves on the market in the long term. Still, most investments are from Asia, but the European market is increasing the demand for internal production by increasing internal market expansion. Most of the initiatives are motivated by the growing market of the Electric Vehicles but in the future also the increasing of batteries for ship usage will contribute to reinforce this trend.
An analysis of battery manufacturing process,	The most important part of the process in terms of costs and time are aging and formation, therefore improving this step would

also considering the cost, time, and energy consumption required;	improve the complete process. In terms of energy consumption, the most important parts are drying and solvent recovery. So applying different techniques and decreasing the energy consumption of this level would decrease the cost of the full process.
A list of steps, skills and requirements for the on-board integration of battery systems	The chapter lists all the implications of using the lithium battery on board the ship. Considering that both the associated electronic equipment and the storage system must be suitable for the marine environment with particular attention to enhanced safety restrictions with respect to land plants. Recommendations and standards of the Class Society were collected and described in the chapter for a correct, safe and efficient usage of batteries integration with other systems on board ships.
An analysis of current recycling strategies and policies for batteries;	Chapter provided and exhaustive analysis starting form two possible scenario for end of life of batteries used on board ships, recycling and reuse of spent lithium-ion batteries due to the sustainability, procurement, and resource circulation. While reuse of batteries (i.e. on land power plant for buffer energy storage) can be useful, and beneficial for circular economy Recycling LIBs can secure raw materials supply for energy storage systems; consequently, reducing energy usage and environmental emission impact from battery life cycle. The potential net gain from recycling is between 5 and 15 Euros/kWh, based on the actual processes. With an increasing recycling in the future, different recycling costs, like for logistics or removal from vehicle, might decrease, which will enhance the attractiveness of the material recovery.
A Life Cycle Analysis (LCA) for two case studies, considering the possible integration of battery systems for different purposes.	A simplified Life Cycle Analysis methodology was used to compare different two ship solution in different scenario. A small ferry which energy is completely provided by batteries (propulsion and hotel loads) with a conventional Internal Combustion Engine one, and a large ferry in which batteries are used for maneuvering during last mile to port or to stay in port when moored at zero emission. Environmental impact is absolutely considerable in case of small ferry completely operated by batteries as emission in operating place is completely reduced to zero. In large ferry, the major source of emission is due to fuel burnt during operation for propulsion. The advantage from batteries is negligible in absolute terms but it is obtained in port and during last mile operation. Commonly ferry port are inside city center so obtaining a considerable reduction of emission in this area certainly worth the investment. From an economical perspective the most advantageous scenario seems to be the use of batteries to provide energy during stop in port without needs of cold ironing. If we intend to pursue the most environmental advantage the best scenario is a cold ironing powered by completely green energy and batteries used for last

	mile from and to the mooring port. The cost of electricity at cold ironing has a negative impact on Net Present Value as the cost for land energy is charged by various external costs which make the final price not comparable with Medium Diesel Oil price. If these extra charges will be reduced the advantage to use of batteries will cover also the extra cost for initial investment.

Table 8 Main document outcomes

4.2 Recommendations

A more commercial aspect that could help in this sense could be that of inserting a clause in the battery supply contracts for the recovery of the system once it has reached the end of its operational life. In fact, often battery systems do not reach a real end of life, but substantially at a level of insufficient energy capacity to effectively perform the work for which they were initially used. Before reaching the recycling phase, it would be possible to use these systems (often with residual capacities between 60 and 80% of the nominal to perform other functions (so-called "second life"), such as energy backup and services to the national electricity grid or as energy storage to reduce the uncertainty of renewable resources (photovoltaic and wind). Inserting a recovery clause for the second life already in the system supply contract could be economically interesting for the customer (who would see a partial economic compensation linked to the disposal of the battery) and opening new businesses to the battery suppliers themselves, as well as decreasing the environmental impact of the battery life cycle (as highlighted in the LCA analysis proposed in this paper).

Still from an economic point of view, a strong recommendation that must be made, especially with a view to decarbonising short and medium-range ships, is to reduce or eliminate taxes on electricity supplied by the European electricity network, in order to incentivize the use (and therefore the conversion of ships) among ship-owners, as happened in many European countries with renewable resources with feed-in tariffs between 2010 and 2020. This would have both a beneficial effect on the development of battery systems on board ships and on the environmental impact of maritime transport, making Europe the centre of gravity of the future market for batteries for marine use, also with a view to local development of the entire supply chain of the battery industry.

Finally, analysing the results of the LCA on the two case studies in the different configurations, it is highlighted how:

- the use of renewable electricity from the terrestrial electricity grid could eliminate the (Global Warming Potential) GWP of ships,
- the use of batteries at berth in port areas without a cold ironing facility, could considerably limit the total energy required to operate with the ship in its lifetime,
- the use of batteries for stay at berth in support to cold ironing and for last mile may be advantageous from an environmental point of view for long range applications,
- on the other hand, the use of batteries recharged from the terrestrial network (especially through renewable resources) is advantageous for boats with short and medium range of action.

5 Deviations from Grant Agreement Annex 1

There are no deviations with respect to Annex 1.

6 References

[1] N. Lebedeva, F. D. Persio e L. Boon-Brett, «Lithium-ion battery value chain and related opportunities for Europe,» JRC Science for Policy Report, 2017.

[2] D. Blagoeva, C. Pavel, D. Wittmer, J. Huisman e F. Pasimeni, «JRC - Materials dependencies for dual-use technologies relevant to Europe's defence sector,» JRC Science for Policy Report , 2019.

[3] J. Huisman, T. Ciuta, F. Mathieux, S. Bobba, K. Georgitzikis e D. Pennington, «RMIS - Raw Materials in the Battery Value Chain,» JRC Scientific Information Systems and Databases, 2020.

[4] J. Fraser, N. Brewster, J. Bedder, J. Anderson, J. Lazuen, O. Masson, Y. Lu e O. Heathman, «Study on future demand and supply security of nickel for electric vehicle batteries,» ROSKILL, 2021.

[5] BASF, «www.basf.com,» [Online]. Available: https://www.basf.com/global/en/media/news-releases/2020/11/p-20-359.html. [Consultato il giorno 29 March 2021].

[6] «www.infinitylithium.com,» [Online]. Available: https://www.infinitylithium.com/the-european-story. [Consultato il giorno 29 March 2021].

[7] «https://www.eba250.com/,» European Battery Alliance 250, [Online]. Available: https://www.eba250.com/verkor-europes-new-battery-cell-producer-begins-its-industrial-journey/. [Consultato il giorno 29 03 2021].

[8] greencarcongress, «www.greencarcongress.com,» [Online]. Available: https://www.greencarcongress.com/2019/10/20191018-catl.html. [Consultato il giorno 29 March 2021].

[9] «www.electrive.com,» [Online]. Available: https://www.electrive.com/2019/02/04/catl-plans-up-100-gwh-battery-factory-in-germany/. [Consultato il giorno 29 March 2021].

[10] «https://seekingalpha.com,» [Online]. Available: https://seekingalpha.com/article/4265367-european-battery-plant-expansion-and-implied-lithium-demands. [Consultato il giorno 29 March 2021].

[11] VW, «https://www.volkswagenag.com/,» [Online]. Available: https://www.volkswagenag.com/en/news/2021/03/power-day--volkswagen-presents-technology-roadmap-for-batteries-.html. [Consultato il giorno 29 30 2021].

[12] Total, «www.total.com,» [Online]. Available: https://www.total.com/media/news/press-releases/groupe-psa-and-total-create-automotive-cells-company-joint-venture. [Consultato il giorno 29 03 2021].

[13] H. Helgesen, «Study on electrical energy storage for ships,» EMSA European Maritime Safety Agency, 2020.

[14] W. H. R. L. A. M. F. D. a. K. D. A. Kwade, "Current status and challenges for automotive battery production technologies," *Nat. Energy,* no. 3, p. 290–300, 2018.

[15] R. Z. J. W. a. Y. W. Y. Liu, «Current and future lithium-ion battery manufacturing,» *iScience,,* vol. 24, n. 4, 2021.

[16] P. A. N. K. G. G. a. D. W. D. S. Ahmed, «Energy impact of cathode drying and solvent recovery during lithium-ion battery manufacturing,,» *J. Power Sources,* vol. 322, 2016.

[17] X. Q. Z. P. S. a. Q. Z. T. Li, «Fluorinated Solid-Electrolyte Interphase in High-Voltage Lithium Metal Batteries,» *Joule,* vol. 3, n. 11, 2019.

[18] J. L. a. S. J. A. D. L. Wood, «Formation Challenges of Lithium-Ion Battery Manufacturing,» *Joule,* vol. 3, n. 12, 2019.

[19] S. A. K. G. G. a. D. W. D. P. A. Nelson, «Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles,» 2019.

[20] H. H. H. e. al., «"The Effects of Mechanical and Thermal Loads during Lithium-Ion Pouch Cell Formation and Their Impacts on Process Time,» *Energy Technol.,* vol. 8, 2020.

[21] Y. D. T. L. a. F. Y. C. Yuan, «Manufacturing energy analysis of lithium ion battery pack for electric vehicles,,» *CIRP Ann. - Manuf. Technol.,* vol. 66, n. 1, p. 53–56, 2017.

[22] N. P. a. A. B. M. Stich, «Drying and moisture resorption behaviour of various electrode materials and separators for lithium-ion batteries,» *J. Power Sources,* vol. 364, 2017.

[23] W. H. a. A. K. F. Huttner, «The Influence of Different Post-Drying Procedures on Remaining Water Content and Physical and Electrochemical Properties of Lithium-Ion Batteries,» *Energy Technol.,* vol. 8, n. 2, 2020.

[24] J. Warner, The handbook of lithium-ion battery pack design: Chemistry, components, types and terminology., 2015.

[25] S. Narayanaswamy, «Design, Modeling and Implementation of Distributed Architectures for Modular Battery Packs,» p. 183, 2018.

[26] T. B. H. v. H. T. L. R. W. D. D. a. D. U. S. S. Rothgang, «Modular battery design for reliable, flexible and multi-technology energy storage systems,» *Appl. Energy,* vol. 137, 2015.

[27] S. SDI, «The Composition of EV Batteries: Cells? Modules? Packs? Let's Understand Properly!,» 2020. [Online]. Available: https://www.samsungsdi.com/column/all/detail/54344.html.

[28] W. Cai, «Lithium-ion battery manufacturing for electric vehicles: A contemporary overview,» *Advances in Battery Manufacturing, Services, and Management Systems,* 2016.

[29] «The Chevy Bolt Battery Pack Possibilities,» 2015. [Online]. Available: GM-VOLT.com.

[30] T. Economics, «Trading economics,» [Online]. Available: https://tradingeconomics.com/. [Consultato il giorno 18 05 2021].

[31] W. Bernhart, «Recycling of Lithium-Ion Batteries in the Context of Technology and Price Developments,» *ATZelectronik,* pp. 38-43, 2019.

[32] A. Leyland, «www.benchmarkminerals.com/,» [Online]. Available: https://www.benchmarkminerals.com/membership/lithium-ion-battery-cell-prices-fall-to-110-kwh-but-raw-material-risk-looms-large-2/. [Consultato il giorno 18 05 2021].

[33] R. Sommerville, P. Zhu, M. A. Rajaeifar, O. Heidrich, V. Goodship e E. Kendrick, «A qualitative assessment of lithium ion battery recycling processes,» *Resources, Conservation and Recycling,* vol. 165, 2021.

[34] X. Zheng, Z. Zhu, X. Lin, Y. Zhang, Y. He, H. Cao e Zhi, «A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries,» *Green Industrial Processes,* 2018.

[35] D. Tan, P. Xu e Z. Chen, «Enabling sustainable critical materials for battery storage through efficient recycling and improved design: A perspective,» *MRS Energy & Sustainability,* 2020.

[36] V. Henze, «https://about.bnef.com,» BloombergNEF, [Online]. Available: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/. [Consultato il giorno 29 03 2021].

[37] «https://www.rolandberger.com/,» roland Berger, [Online]. Available: https://www.rolandberger.com/en/Insights/Publications/Battery-recycling-is-a-key-market-of-the-future-Is-it-also-an-opportunity-for.html. [Consultato il giorno 29 03 2021].

[38] L. Gaines, «The future of automotive lithium-ion battery recycling: Charting a sustainable course,» *Sustainable Materials and Technologies,* 2014.

[39] X. Chen, B. Fan, L. Xu, T. Zhou e J. Kong, «An atom-economic process for the recovery of high value-added metals from spent lithium-ion batteries,» *Cleaner production,* 2015.

[40] X. Zheng, J. Li e N. Singh, «Recycling of Spent Lithium-Ion Battery: A Critical Review,» *Environmental Science and Technology,* 2014.

[41] Vector Ltd, «Batteries & the circular economy,» in *New energy future*, 2019.

[42] B. N. E. F. BNEF, «Global storage market to double six times by 2030,» 2017. [Online]. Available: https://about.bnef.com/blog/global-storage-market-double-six-times-2030/..

[43] European Commission, Joint Research Centre, «Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles,» 2019.

[44] E.Elkind, «How to save money and clean the grid with second-life electric vehicle batteries,» *UCLA Law / Berkeley Law,* 2014.

[45] Ricardo Energy & Environment, «Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves,» 2016.

[46] B. N. E. F. BNEF, «Liebreich and McCrone: Electric vehicles – It's not just about the car,» 2016. [Online]. Available: https://about.bnef.com/blog/liebreich-mccrone-electric-vehicles-not-just-car/.

[47] B. N. E. F. BNEF, «China's Giving Batteries a Second Life,» 2018. [Online]. Available: https://www.bloomberg.com/view/articles/2018-03-11/china-s-giving-batteries-a-second-life.

[48] J. R. C. European Commission, «Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB),» 2018.

[49] E. E. M. S. A. -. D. G. A. M. E. Advisor, «2019-0217, Rev. 04 Electrical Energy Storage for Ships,,» 2020.

[50] Maritime Battery Forum, «Life cycle assessment of batteries in maritime sector,» 2016.

[51] Re2Live, «www.re2live.be,» [Online]. Available: http://re2live.be/. [Consultato il giorno 17 05 2021].

[52] eco2lib, «www.eco2lib.eu,» [Online]. Available: https://www.eco2lib.eu/about-us/. [Consultato il giorno 18 05 2021].

[53] «https://www.tu-braunschweig.de/,» TU Braunschweig, [Online]. Available: https://www.tu-braunschweig.de/en/aip/pl/research/current-research-projects/details-current-research-projects/lithorec-and-lithorec-ii. [Consultato il giorno 14 04 2021].

[54] T. Braunschweig, «https://www.erneuerbar-mobil.de,» 29 04 2021. [Online]. Available: https://www.erneuerbar-mobil.de/sites/default/files/publications/abschlussbericht-lithorec_1.pdf.

[55] T. Braunschweig, «https://www.erneuerbar-mobil.de/,» 29 04 2021. [Online]. Available: https://www.erneuerbar-mobil.de/sites/default/files/2017-01/Abschlussbericht_LithoRec_II_20170116.pdf.

[56] globenewswire, «www.globenewswire.com,» 08 03 2021. [Online]. Available: http://www.globenewswire.com/en/news-release/2021/03/08/2188458/28124/en/Global-Lithium-Ion-Battery-Recycling-Market-Report-2021-Market-was-Valued-at-403-77-Million-in-2019-and-is-Projected-to-Reach-1-392-84-Million-by-2027.html. [Consultato il giorno 18 05 2021].

[57] EU, «DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,» *Official Journal of the European Union,* 2006.

[58] EU, «DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,» *Official Journal of the European Communities,* 2000.

[59] E. commission, «https://ec.europa.eu,» [Online]. Available: https://ec.europa.eu/environment/topics/waste-and-recycling/batteries-and-accumulators_en. [Consultato il giorno 18 05 2021].

[60] BALANCE Technology Consulting, «LCPA Life Cycle Performace Assesment Tool,» [Online]. Available: https://lcpa.bal.eu/BALLCPA_Webseite/.

[61] D. GL, «EMSA MARITIME BATTERY STUDYElectrical Energy Storage for ShipsEMSA European Maritime Safety Agency,» 2019.

[62] E. COMMISION, «2019 Annual Report on CO2 Emissions from Maritime Transport».

[63] &. J. J. G. Reid., «Second Life-Batteries As Flexible Storage,» in *For Renewables Energies. Kurzstudie im auftrag des Bundesverbandes Erneuerbare Energy E.V. und der Hannover Messe*, 2016.

6.1 Index of Figures

6.2 Index of Tables

7 Acknowledgements and disclaimer

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner	Partner Full Name
1	FM	FLANDERS MAKE
2	DAMEN	SCHEEPSWERF DAMEN GORINCHEM BV
3	FCSI	FINCANTIERI SI SPA
4	RINA	RINA SERVICES SPA
5	SOERMAR	FUNDACION CENTRO TECNOLOGICO SOERMAR
6	VARD	VARD ELECTRO AS
7	ABEE	AVESTA BATTERY & ENERGY ENGINEERING
8	IMECAR	IMECAR ELEKTRONIK SANAYI VE TICARET LIMITED SIRKETI
9	UNR	UNIRESEARCH BV
10	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
11	Fraunhofer	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
12	IKERLAN	IKERLAN S. COOP
13	MGEP	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP
14	SINTEF	SINTEF ENERGI AS
15	POLITO	POLITECNICO DI TORINO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963560. The information and views set out in this publication does not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

8 Appendix A - Table of Abbreviations

Abbreviation	
BC	Black Carbon
CBDR	Common But Differentiated Responsibilities
CCC	Sub-Committee on Carriage of Cargoes and Containers
CII	Carbon Intensity Indicator
CO2	Carbon Dioxide
DWT	Deadweight Tonnage
ECA	Emission Control Area
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EIAPP	Engine International Air Pollution Prevention
EIV	Estimated Index Value
EMSA	European Maritime Safety Agency
ETS	Emissions Trading System
EU	European Union
GHG	GreenHouse Gas
GRT	Gross Register Tonnage
GT	Gross Tonnage
HCFC	Hydrochlorofluorocarbons
HFO	Heavy Fuel Oil
HIS	
HSFO	High-Sulfur Fuel Oils
HVAC	Heating, Ventilation and Air Conditioning
IAPP	International Air Pollution Prevention
IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-Based Measures
MEPC	Marine Environment Protection Committee
MRV	Monitoring, Reporting and Verification
NGO	Non-Governmental Organizations
Nox	Nitrogen oxides
PM	Particulate Matter
RO	Recognized Organisation
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
Sox	Sulphur oxide
VOC	Volatile Organic Compounds