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Solutions for large batteries for waterborne transport

GRANT AGREEMENT No. 963560

D1.3 – Road map for battery productions and cost targets

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Author	Driss Madouch (FCSI)	2021-06-28
WP leader	Andrea Lombardi (FCSI)	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)	2021-06-30

Report details

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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 evidenced by several studies by international consultants and refocusing research centres on environmental and technological issues, batteries will play a fundamental role in the decarbonisation of transport systems.

For light road transport and short sea shipping, the conversion of the European and world fleet from internal combustion engines to battery electric vehicles (BEVs) is already underway.

For heavy duty vehicles (including medium and long range maritime transport) batteries are a fundamental technology to enable the use of the technologies under study for the decarbonisation of these systems (fuel cells, alternative sustainable fuels, etc.).

Therefore, the activity of this task of the SEABAT project is aimed to:

- Define a roadmap of the costs and production volumes of battery systems for marine use, also defined the targets that need to be reached,
- Identify the main European big players in battery systems,
- Define the main skills required today and in the future for the development and integration of battery systems on board ship,
- Identify the main challenges and bottlenecks for shipboard integration of battery systems.

The main results of the research analysis regarding the roadmap of costs have highlighted a future cost target of the battery system for marine use of approximately 250-300 € / kWh (complete system) with production volumes that should settle between 3 and 4 GWh of installations,

Meanwhile the main bottlenecks the main bottlenecks concern: patents and certification for personnel, temperatures and humidity (especially in some regions with extreme weather conditions) and external fire.

Moreover, the main challenges, especially for the full decarbonisation, are: the cost of onshore energy (with the need to get tax-free rates to be competitive with traditional fuels), battery cost, specific energy and ageing, which have a direct impact on the possible integration on board of large volumes of batteries and on their expected lifespan, and related replacement costs.

Contents

1 Introduction

Transport represents one fourth of the total CO_2 emissions in the EU (as proposed in Figure 1). Furthermore, as transport demand continues to grow, the EU transport emissions have increased by around 20% compared to 1990 levels, while the EU total emissions have decreased by around 20% in the same period (see Figure 2).

Further, considering the equivalent CO_2 emissions due to passenger travel, trains are the most efficient transport system in the EU, with GHG emissions per pkm that are only a fraction of most other modes (as shown in Figure 3). In this context, the second most efficient mode is maritime passenger transport. However, the value presented here mainly represents emissions from roll-on/roll-off ferries designed to carry both vehicles and passengers (RoPax). The detailed results show that emissions from other passenger vessel types, such as cruise ships, can be much higher.

On the other hand, GHG efficiency rates for freight transport vary much more than those for passengers. So much so that a logarithmic scale was used in the left part of Figure 4. The relevant unit is tonne-km, which means moving the payload of one tonne over one kilometre. Emissions for freight transported by maritime shipping, rail and inland waterway are very low compared with those for freight transported by heavy goods vehicle (HGV). Air cargo stands out as the mode with the highest emissions by far. However, over the 2014-2018 period, air cargo saw the biggest GHG efficiency improvement (12%) followed by rail freight (11%) [1].

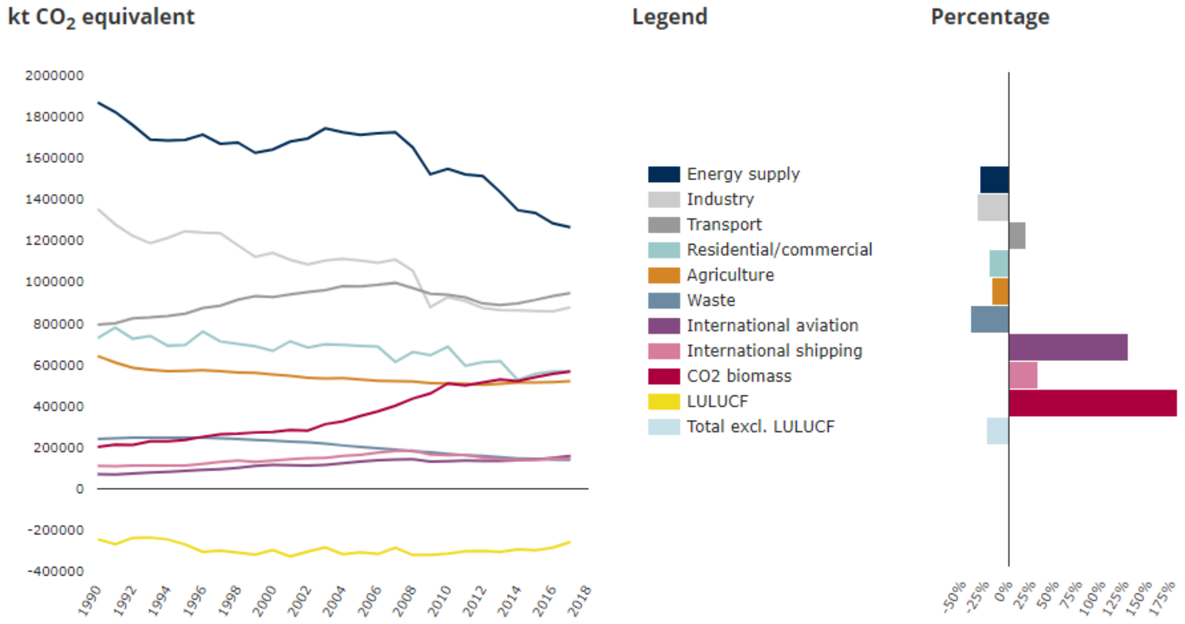


Figure 1 – CO2 equivalent emissions per sectors in EU (Source: https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5#tab-dashboard-02)

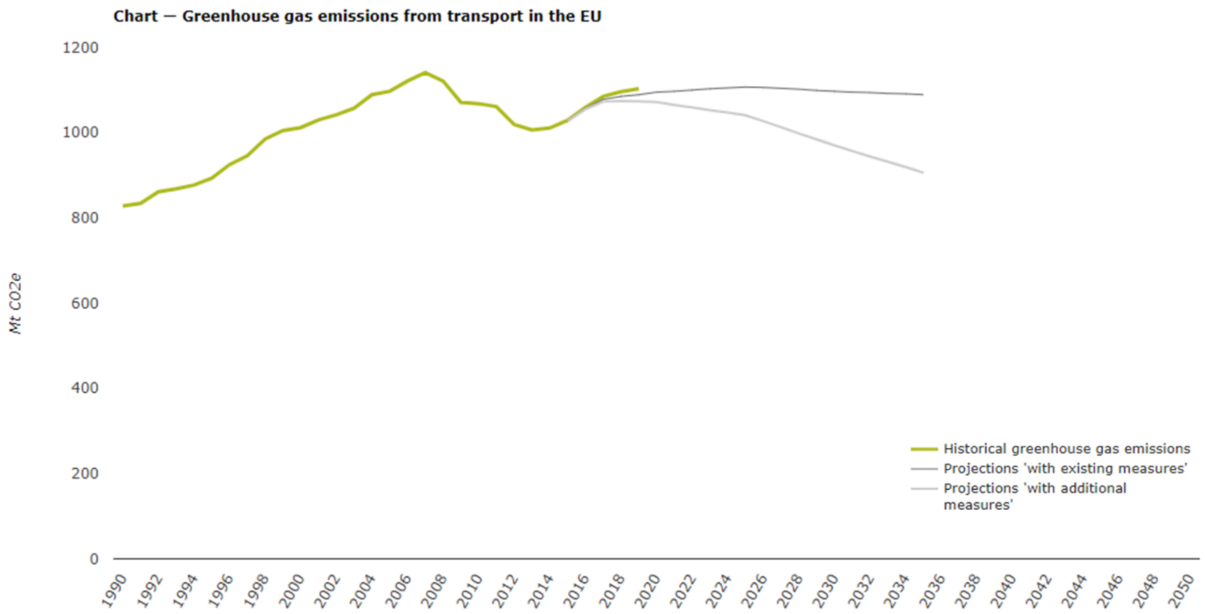
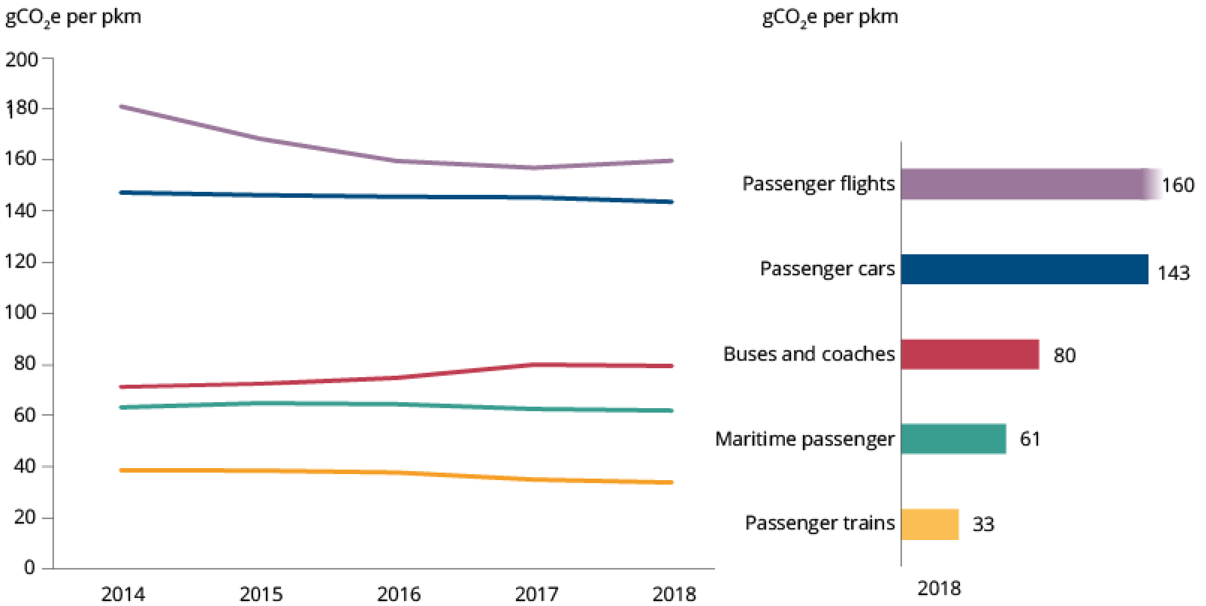
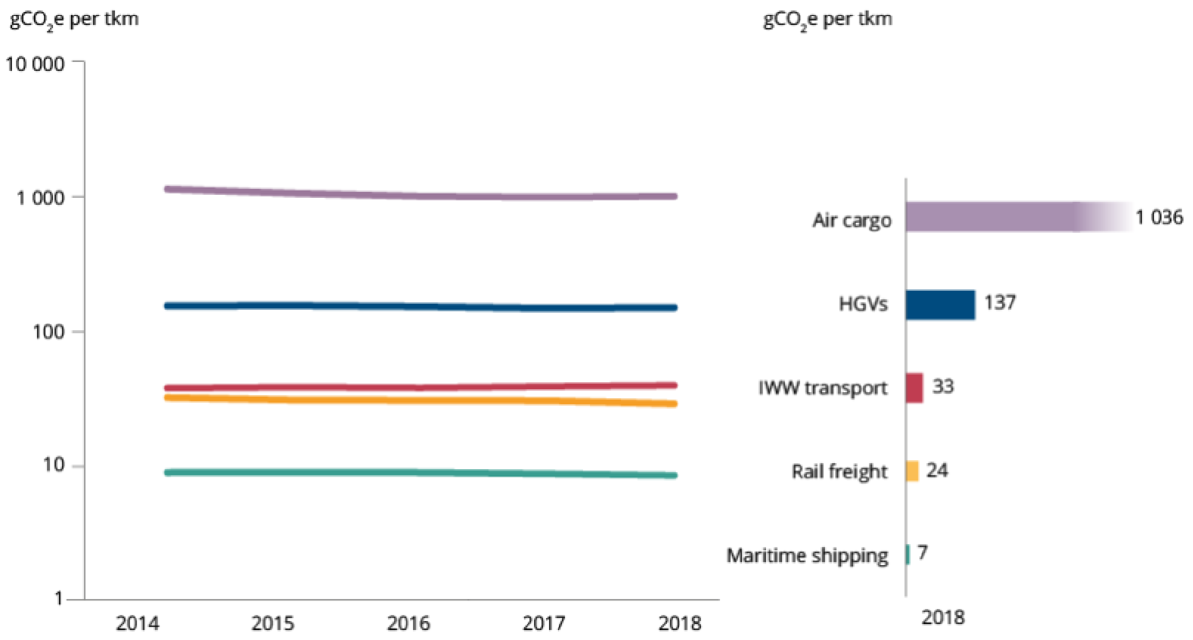


Figure 2 – CO2 equivalent emissions due to transportation in EU (source: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases-7/assessment)



Source: Fraunhofer ISI and CE Delft, 2020
Notes: pkm = passenger kilometre; implied car occupancy rate: 1.6

Figure 3 – Average GHG emissions by motorised mode of passenger transport, EU-27, 2014-2018 (Source: https://www.eea.europa.eu/publications/rail-and-waterborne-transport)



Source: Fraunhofer ISI and CE Delft, 2020
Note: logarithmic scale used in left chart; tkm = tonne kilometre

Figure 4 – Average GHG emissions by motorised mode of freights transport, EU-27, 2014-2018 (Source: https://www.eea.europa.eu/publications/rail-and-waterborne-transport)

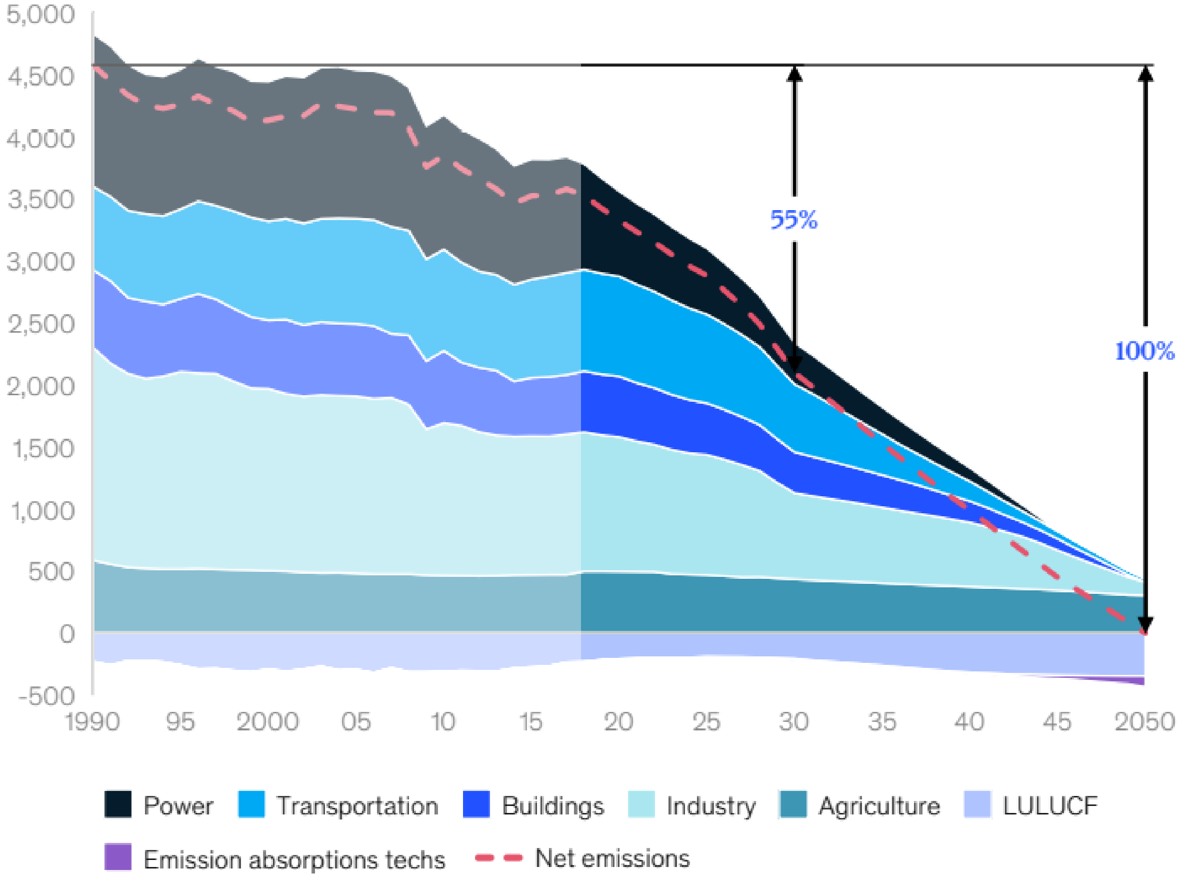


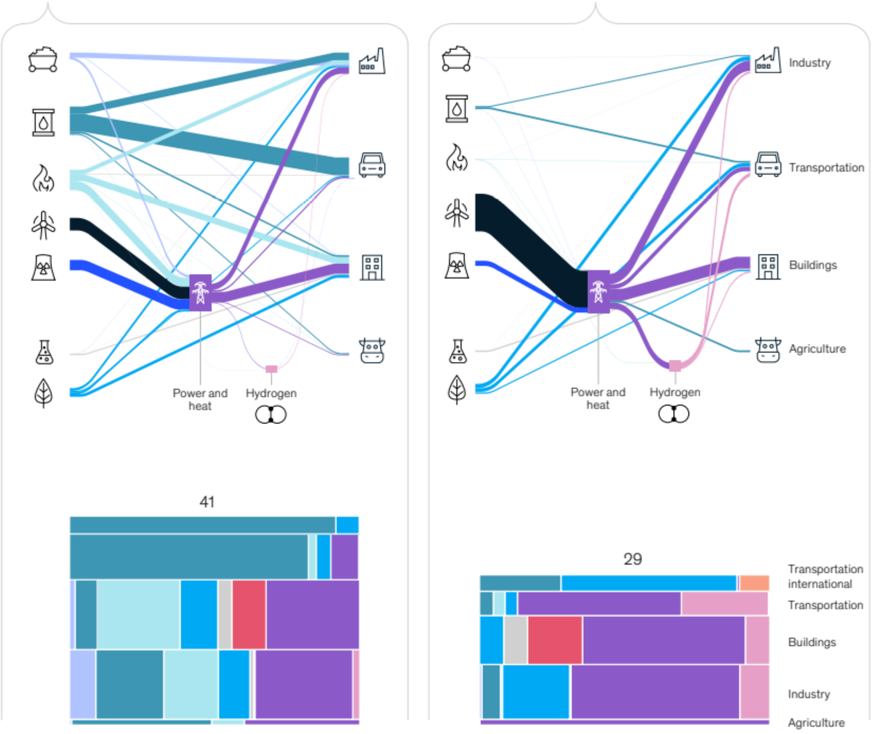
Figure 5 – cost optimal roadmap for decarbonization of EU [2]

By 2030, some 64 percent of the European Union's emissions reduction would be achieved by large-scale electrification and increases in energy efficiency, accounting for 47 percent and 17 percent, respectively [2]. As summarized in Figure 6, the power sector would become the central switchboard of the climate-neutral EU energy system, especially for transportation systems, which would rely on electricity both for battery vehicle and vehicle powered by Sustainable Alternative Fuels (SAF) generated by renewable electric sources (i.e. green hydrogen based fuels).

In such a context, different solutions for the decarbonization of EU (and shipping) offers different abatement cost, as proposed in Figure 7. In fact, in road transportation, the required technologies are already in the early-adoption phase, so the abatement cost is negative in Figure 7 (meaning that an economical return is expected).

However, scaling supply chains that could support the transition to 100 percent BEV (Battery Electric Vehicle) sales, from mining the raw materials for batteries to assembling EVs, is at least a decade-long process. This limits the sector's short-term abatement potential to 30 percent by 2030. After 2030, BEV and hydrogen supply chains could be at scale, accelerating decarbonization. By 2045, more than 95 percent of today's transportation emissions could be abated.

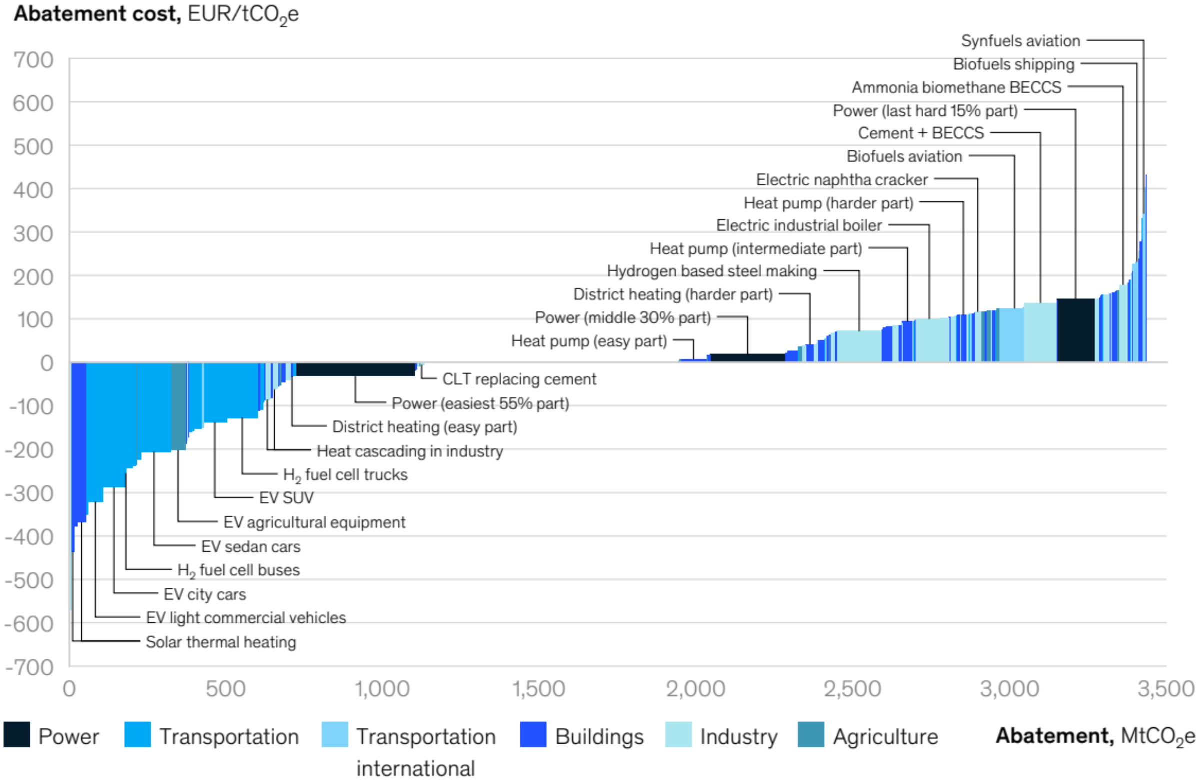
Aviation and shipping are the exceptions because they have fewer scalable low-carbon alternatives (mainly based on the use of sustainable alternative fuels combined with batteries) and would need to rely on the more expensive option of switching SAF to decarbonize by 2050, as shown in Figure 7, where the abatement cost is expected to be between 200 and 350 €/tCO_2eq.



1. Includes solar PV, solar thermal, wind power, and hydro power
2. Other miscellaneous sources, e.g. non-renewable waste

Source: McKinsey

Figure 6 – Primary energy demand to final energy consumption in EU [2]



1. Weighted average

Source: McKinsey, UNFCCC

Figure 7 – 2050 abatement cost curve [2]

1.1 Purpose of the document

As highlighted on Deliverable 1.2 of SEABAT project, the medium and large application range of batteries for maritime applications will see a considerable increase in their market share over the next 5-10 years, with their shares stabilizing over a 15-year horizon. In the medium term, on the other hand, technological innovations should make it possible to carry out (short) operational scenarios with zero emissions both for large and medium-small ships.

In such a general context, the main aim of this document is to provide a roadmap for future cost and production volumes of batteries for maritime applications. This, in the general picture of the SEABAT project, is seen as input information to WP2 (Specification and requirements) and WP3 (Modular and scalable battery system), by defining the future needs and requirements of battery systems (i.e. performances, costs and production volumes).

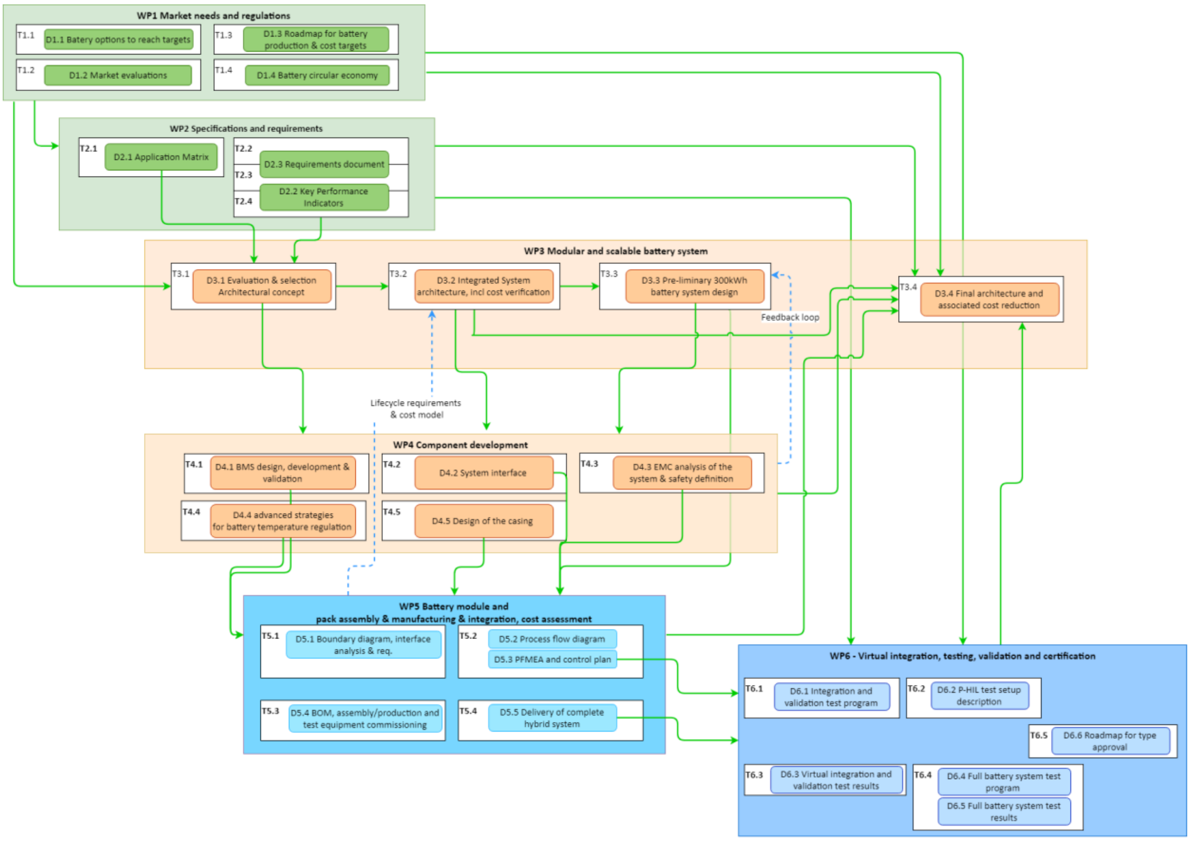


Figure 8 - Workpackages structure

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 the document.

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

- A metrics to evaluate the energy storage technology cost and performance;
- A roadmap for the battery cost on the next years;

- A list of the main international players and their strategies for future;
- A Roadmap for battery production on the next years;
- A list of required skills for battery production and installation on board;
- A list of challenges and bottleneck for future.

Finally, **Chapter 4** draws some conclusions and proposes recommendations for the next tasks of Work Package 1.

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 D1.3.

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 D1.3 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 cost target definition for maritime batteries, the challenges, bottlenecks and required skills definition.
- **Damen**, as contributor on cost target definition and roadmap development.
- **SOERMAR**, as contributor on roadmap development and current cost of batteries identification.
- **ABEE,** as contributor on roadmap development, current cost of batteries and required skills identification .

3 Results

This paragraph is mainly focused on the presentation and analysis of the results obtained. Particular attention is paid to the technical-economic roadmap relating to the costs and production volumes of batteries for marine use in the near future, also defining the main targets, the bottlenecks towards and the skills required for the large-scale use of these systems.

3.1 Energy storage technology cost and performance metrics

To define the roadmap of battery costs, it is necessary as a first step to define a methodology for their identification and subdivision. For this purpose, being an effective and well described method, it has been decided to use the methodology defined by the U.S. Department of Energy (DOE), according to the report: “Energy Storage Technology and Cost Characterization”, which has been developed by the Pacific Northwest National Laboratory, operated by Battelle for the DOE, Argonne National Laboratory, operated by Chicago Argonne, LLC; and Oak Ridge National Laboratory, operated by UT-Battelle, LLC; and supported by the HydroWIRES Initiative of DOE’s Water Power Technologies Office [4].

Metrics include those related to capital costs and the costs of power conversion system (PCS), balance of plant (BOP), construction and commissioning (C&C), fixed and variable operations and maintenance (O&M). Performance metrics include round-trip efficiency (RTE), response time, cycle life, calendar life, manufacturing readiness level (MRL) and technology readiness level (TRL), as described below.

3.1.1 capital cost ($/kWh or $/kW)

Capital cost, as defined here, covers different components that vary by technology type. For batteries and capacitors, capital costs pertain to the procurement of the direct current (DC) energy storage unit and do not include power conversion system, balance of plant, or construction and commissioning costs. Capital costs for electrochemical storage devices are typically expressed in dollars per kilowatt hour ($/kWh). While ultracapacitors are electrochemical devices, their total cost can be represented as either $/kW or $/kWh based on the application.

For electrochemical storage units, the capital cost reported within this document includes electrodes, electrolytes, and separators.

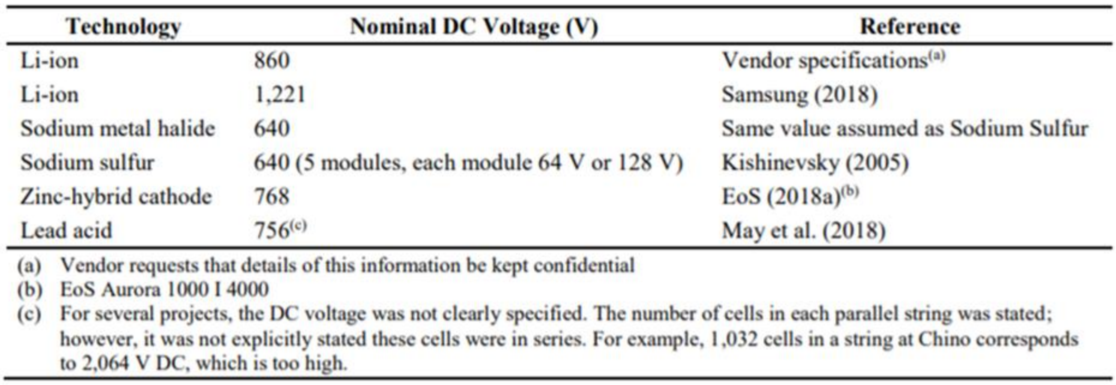
Lahiri (2017) estimated the cost range for the DC-side modules and battery management system for battery systems to be in the range of $325–$700/kWh, keeping the values broad to accommodate technology differences. Currently, li-ion battery systems have the lowest capital costs, reaching as low as $200/kWh (Kamath 2016) due to experience and supply chain development in support of the consumer electronics and automotive markets. Other less mature electrochemical systems, such as sodium-sulfur, have a higher capital cost. Aquino et al. (2017) provided a range of values for a 4 MW/16 MWh sodium-sulfur system with the low end being $500/kWh to $1,000/kWh for just the battery cost.

3.1.2 Power Conversion System, PCS ($/kW)

This component of battery energy storage systems includes the cost for the inverter and packaging, as well as container and inverter controls. The power conversion system cost is expected to decrease as system voltages increase, because higher current for the same power rating leads to higher cost.

In addition to voltage-related costs, which fall under the system design bucket, Power conversion system standardization and manufacturing scale are further expected to drive down costs. For the Li-ion technology, the cost is assumed to be 90 percent of other technologies due to its higher DC voltage range. However, by 2025, it is assumed that all other battery technologies will have caught up in terms of increasing the DC operating voltage range. A 25 percent decrease in cost over present-day Li-ion power conversion system cost is assigned to year 2025 because of the benefits of standardization and scalability due to increased volume production. The lower 2025 cost is assigned uniformly to power conversion system for all battery chemistries. This assumption is supported by developments such as flow batteries efficiently addressing shunt current related issues to increase DC string voltage. Similarly, sodium-based high temperature systems, with their higher unit cell voltage than flow battery cells, are well placed to scale up to higher DC voltage levels in the coming years.

While new technologies such as SiC may mature by 2025, they may not yet benefit from large-volume production.



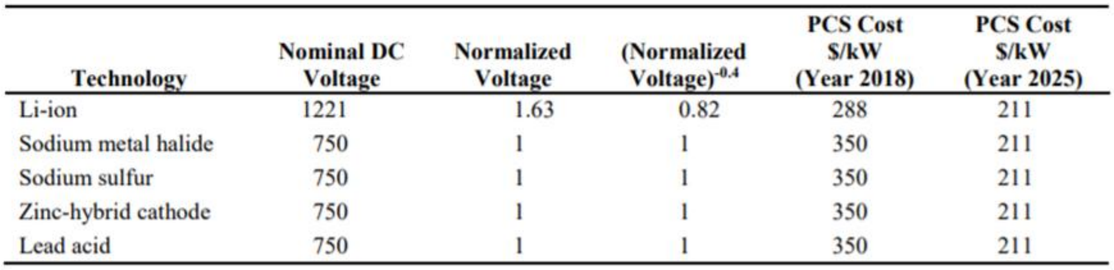
Technology	Nominal DC Voltage (V)	Reference
Li-ion	860	Vendor specifications$^{(a)}$
Li-ion	1,221	Samsung (2018)
Sodium metal halide	640	Same value assumed as Sodium Sulfur
Sodium sulfur	640 (5 modules, each module 64 V or 128 V)	Kishinevsky (2005)
Zinc-hybrid cathode	768	EoS (2018a)$^{(b)}$
Lead acid	756$^{(c)}$	May et al. (2018)

(a) Vendor requests that details of this information be kept confidential
(b) EoS Aurora 1000 I 4000
(c) For several projects, the DC voltage was not clearly specified. The number of cells in each parallel string was stated; however, it was not explicitly stated these cells were in series. For example, 1,032 cells in a string at Chino corresponds to 2,064 V DC, which is too high.

Figure 9 – System voltages by technology. **Source: "Energy Storage Technology and Cost Characterization" [2]**

The power conversion system cost ranged from \$130/kW to \$890/kW. The Electric Power Research Institute (EPRI) proposed \$200/kW for small systems and estimated a 50 percent reduction for large-scale systems (even if 50-100 €/kW is currently a good range of cost for power electronics conversion in maritime field). Power conversion system is common across all battery technologies (and ultracapacitors) and will affect all of them similarly.

Based on the above table, the power conversion system costs were obtained by multiplying the power conversion system cost of \$350/kW by the normalized voltage raised to a power of -0.4 as shown in the following illustration. Because the nominal DC voltage for Li-ion chemistry is about 63 percent higher than other technologies (also depending on the Li-ion technology considered), the normalized voltage for other technologies is set to 1 based on a nominal DC voltage of 750 V, while Li-ion chemistry normalized voltage is set at 1221/750 or 1.63. For the year 2025, it is assumed that this difference in nominal DC voltage will no longer persist.



Technology	Nominal DC Voltage	Normalized Voltage	(Normalized Voltage)$^{-0.4}$	PCS Cost \$/kW (Year 2018)	PCS Cost \$/kW (Year 2025)
Li-ion	1221	1.63	0.82	288	211
Sodium metal halide	750	1	1	350	211
Sodium sulfur	750	1	1	350	211
Zinc-hybrid cathode	750	1	1	350	211
Lead acid	750	1	1	350	211

Figure 10 – **Calculated PCS cost (\$/kW), 2018 and 2025. Source: "Energy Storage Technology and Cost Characterization" [2]**

3.1.3 Balance Of Plant, BOP ($/kW)

The balance of the energy storage system (ESS), known as the BOP, typically includes components such as site wiring, interconnecting transformers, and other additional ancillary equipment and is measured on a $/kW basis (DNV GL 2016). Hayward & Graham (2017) provided BOP costs in $/kWh, with the cost being $508/kWh for year 2018 and $441/kWh for year 2025 in 2017. At that high of a cost, the research team believes the estimated cost could include some costs that we would deem to be construction and commissioning costs. Clean Energy Grid (2014) provides a wide range of BOP cost, expressed in $/kWh ($120–$600/kWh).

The BOP costs are mainly assigned to electrical wiring and connections. Unit cell voltage plays a role to the extent that for the same ampere-hour (Ah) capacity, the cell count decreases with increasing voltage, with lower numbers of cell-to-cell interconnections needed. However, most battery systems have basic repeating units or modules, which consist of multiple cells. The module cost is already captured in the DC system cost. Hence, in terms of module interconnections for large systems, the number of modules in the system determine the inter-module connection costs. The series-parallel design within the battery system determines the maximum current between adjacent modules, thus determining the current conductor specifications for a specific material (width, thickness, and length). Even for high cell voltage chemistries such as Li-ion, some vendors choose cells with small Ah capacity to improve reliability and safety.

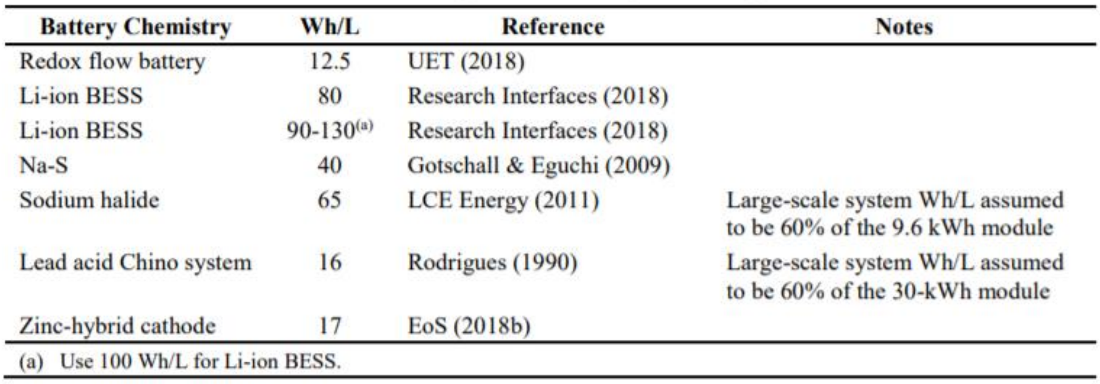
Due to the considerations, the BOP across all battery chemistries has been set at $100/kW. Because no significant technological improvements are anticipated, a nominal 5 percent decrease in BOP costs is assigned for the year 2025 to account for efficiencies associated with scale.

3.1.4 Construction and commissioning, C&C ($/kWh)

Construction and commissioning costs, also referred to as engineering, procurement, and construction costs, consist of site design costs, costs related to equipment procurement/transportation, and the costs of labor/parts for installation (DNV GL 2016). For grid integration, the cost is mainly a function of system footprint and weight (with discrete steps in costs), degree of factory assembly vs. onsite assembly (the total cost may be the same regardless of where the assembly occurs), and architecture in terms of open racks vs. containerized systems.

For this report, construction and commissioning cost was addressed strictly using the system footprint or using the total volume and weight of the battery energy storage system. Volume has been used as a proxy for all these metrics. Footprint in and of itself does not capture the system volume and weight. While volume does not accurately reflect the battery energy storage system weight, it is a better proxy for weight than footprint. For future work, it is recommended that a weighted combination of system footprint, volume, and weight per unit energy be used. For this work, the normalized volume per watt-hour is used as a metric.

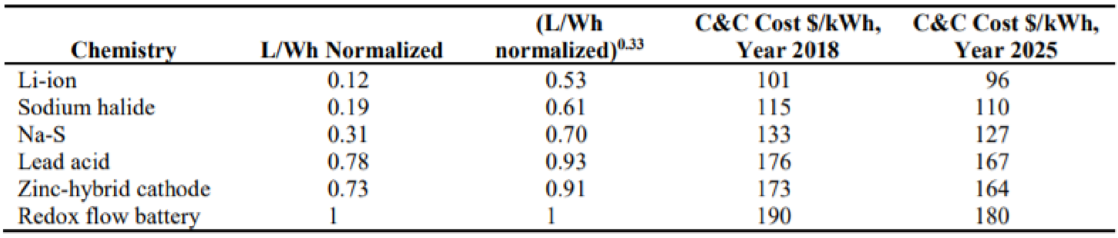
The construction and commissioning costs were increased by 15 percent for the technology with the smallest energy density or largest liters per watt-hour (L/Wh). This value was multiplied by the normalized volume per watt-hour raised to a power of 0.33 to yield a Li-ion construction and commissioning cost of $100/kWh, slightly higher than the $80/kWh estimated by McLaren et al. (2016). A 5% drop was assumed for year 2025 because while gains have been made in recent years, the estimated construction and commissioning cost at $100/kWh is on the low-end of current estimates with little scope for further cost decrease due to “learning”. Additionally, any benefits going further along the learning curve are expected to be partially balanced by higher material and manufacturing costs with increased penetration of storage. Below, you can see the volume of the system and construction and commissioning cost by technology.



Battery Chemistry	Wh/L	Reference	Notes
Redox flow battery	12.5	UET (2018)	
Li-ion BESS	80	Research Interfaces (2018)	
Li-ion BESS	90-130(a)	Research Interfaces (2018)	
Na-S	40	Gotschall & Eguchi (2009)	
Sodium halide	65	LCE Energy (2011)	Large-scale system Wh/L assumed to be 60% of the 9.6 kWh module
Lead acid Chino system	16	Rodrigues (1990)	Large-scale system Wh/L assumed to be 60% of the 30-kWh module
Zinc-hybrid cathode	17	EoS (2018b)	

(a) Use 100 Wh/L for Li-ion BESS.

Figure 11 – System volume by technology. Source: "Energy Storage Technology and Cost Characterization" [4]



Chemistry	L/Wh Normalized	(L/Wh normalized)$^{0.33}$	C&C Cost $/kWh, Year 2018	C&C Cost $/kWh, Year 2025
Li-ion	0.12	0.53	101	96
Sodium halide	0.19	0.61	115	110
Na-S	0.31	0.70	133	127
Lead acid	0.78	0.93	176	167
Zinc-hybrid cathode	0.73	0.91	173	164
Redox flow battery	1	1	190	180

Figure 12 – Construction and commissioning cost by technology. Source: "Energy Storage Technology and Cost Characterization" [4]

3.1.5 Fixed operations and maintenance, fixed O&M ($/kW-yr)

Fixed Operations and Maintenance includes all costs necessary to keep the storage system operational throughout the duration of its economic life that do not fluctuate based on energy usage. This value is normalized with respect to the rated power of the storage system and is expressed as $/kW-yr. Operations and Maintenance costs for all battery chemistries were in the range of $6–$20/kW-yr, with most in the $6–14/kW-yr range (Aquino et al. 2017a and DNV GL 2016). A fixed O&M cost of $10/kW-yr was used for all battery chemistries.

3.1.6 Variable operations and maintenance, variable O&M ($/kW-yr)

Variable Operation and Maintenance includes all costs necessary to operate the storage system throughout the duration of its economic life and is normalized with respect to the annual discharge energy throughput. For this reason, this value is expressed as c$/kWh. Variable O&M costs account for wear and tear of the system during operation. Few resources and sources provided a concrete variable Operation and Maintenance value (Black & Veatch 2012; Aquino et al. 2017a). Those that did assumed it to be approximately 0.3 c$/kWh-year. This report uses this number for variable Operation and Maintenance for other battery technologies. Note that cycle and calendar life for each system, when accounted for properly, provide the correct variable costs as the storage system ages, while incorporation of round-trip efficiency accounts for variable costs related to discharge and the subsequent recharge. Hence, the variable cost of 0.3 c$/kWh, is assumed to be a catch-all for energy throughput-related costs that are not accounted for by cycle/calendar life and round-trip efficiency.

3.1.7 Round-Trip Efficiency, RTE

Round-trip efficiency is the ratio of net energy that is discharged to the grid (after removing auxiliary load consumption) to the net energy used to charge the battery (after including the auxiliary load consumption). Losses for battery energy storage systems can be grouped into the following categories:

- Loss of Ah capacity. While Ah loss can be high over the course of the battery life, it is negligible for each cycle. In flow batteries, cross-over–related losses accumulate over several cycles but are negligible for each cycle.
- Internal resistance-related losses reduce discharge voltage while increasing charge voltage.
- Auxiliary loads such as heating, ventilation, and air-conditioning (HVAC), battery management systems (BMSs), power conversion system controls, and pumps (for flow batteries).

While there is no single round-trip efficiency value for each technology, this work lists DC-DC round-trip efficiency for each technology, and used 0.96 round-trip efficiency for power conversion system to compute the overall system round-trip efficiency for each technology (Newbery 2016). For most cases, the DC-DC round-trip efficiency was used in our alternating current (AC)-AC round-trip efficiency estimates. For some cases, where system round-trip efficiency was available based on our work on grid-scale battery testing and analysis, these values were also used in our round-trip efficiency analysis.

3.1.8 Response Time

Ramp rate is the time (typically in seconds or minutes) that a system takes to change its output level from rest to rated power; faster ramp rates or lower response times are more valuable. Response time, for the most part, is determined by the inverter selection for the application and the overall system design. If response time is critical to operation of a system, the owner of the project can select a power conversion system or DC stack design that can respond at the desired rate. For flow batteries, for example, if the DC stack design is such that it can ramp up to the rated power within one second, it would then be the inverter that determined the response time.

Based on an extensive information review and testing of Li-ion and flow battery systems conducted by the research team, the response times for the DC battery and ultracapacitor energy storage systems contained in this report were assumed to be less than one second. However, extensive tests conducted by the research team have shown that inverter response times can range from as little as less than 1 second to approximately 13 seconds to reach rated power. Therefore, we assume that the response times for the ultracapacitor and the Battery energy storage systems contained in this analysis would be 1 second, subject to power conversion system limitations that could extend the response time out by an additional 1-13 seconds.

3.1.9 Cycle Life

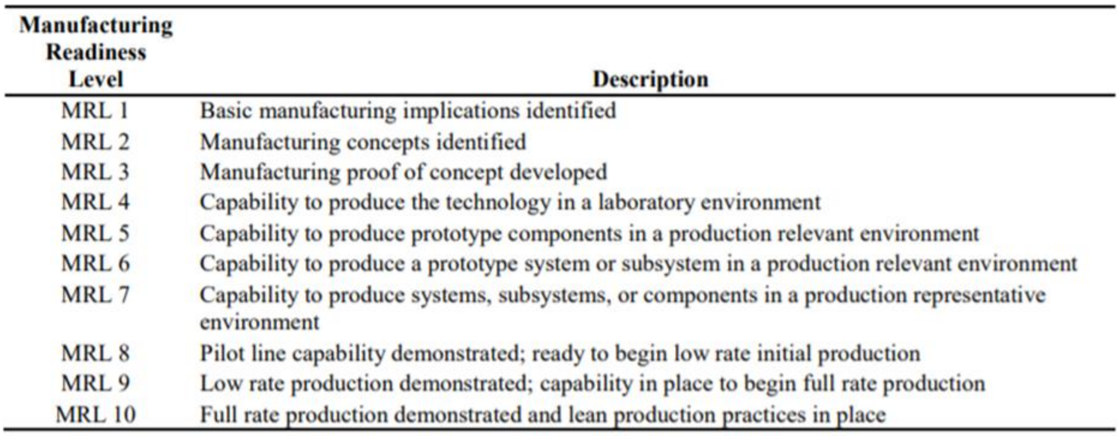
The cycle life for conventional batteries is a function of its depth of discharge (DoD), but the life for a redox flow battery does not depend on depth of discharge. Ultracapacitors have cycle lives >200,000, because chemical degradation is not an issue. The cycle life of batteries was compiled at 80 percent depth of discharge.

3.1.10 Calender Life

Calendar life for batteries is highly dependent on the operating conditions. For batteries and ultracapacitors operating at ambient temperatures, the life decreases with an increase in operating and/or ambient temperature. Calendar life is defined strictly as the maximum life of the system when it is not being operated, because when it is being cycled, depending on the degradation rate of calendar vs. cycle life, one of them determines the overall life of the system. The calendar life used in this work uses data gathered from reposts and from vendors.

3.1.11 Manufacturing Readiness Level (MRL)

Manufacturing readiness level is a measure used for assessing how mature the manufacturing of a product for a technology is and it ranges from a scale of 1 (basic manufacturing issues identified) through 10 (high-rate production using efficient production practices demonstrated). According to the U.S. Department of Defense Manufacturing Readiness Levels Deskbook (DOD 2017), the values represent a "non-linear ordinal scale that identifies what maturity should be as a function of where a program is in the acquisition life cycle." The next illustration, reproduced from the Deskbook, provides an overview of each of the manufacturing scales at which the technologies in this report are measured.

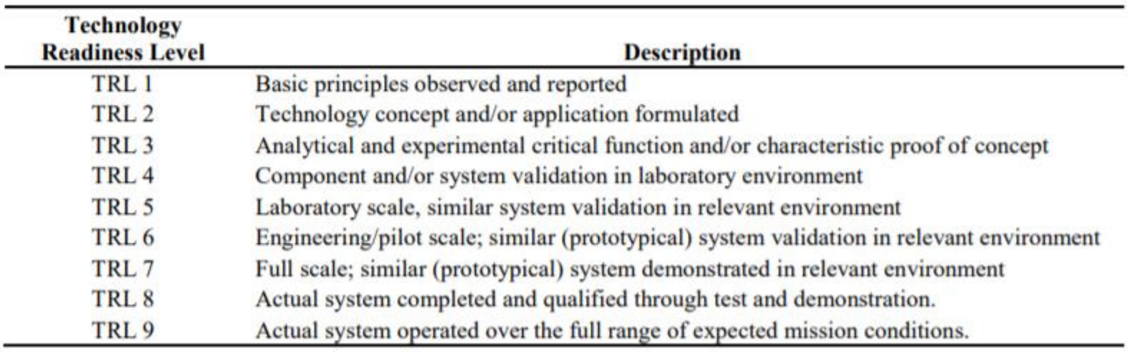


Manufacturing Readiness Level	Description
MRL 1	Basic manufacturing implications identified
MRL 2	Manufacturing concepts identified
MRL 3	Manufacturing proof of concept developed
MRL 4	Capability to produce the technology in a laboratory environment
MRL 5	Capability to produce prototype components in a production relevant environment
MRL 6	Capability to produce a prototype system or subsystem in a production relevant environment
MRL 7	Capability to produce systems, subsystems, or components in a production representative environment
MRL 8	Pilot line capability demonstrated; ready to begin low rate initial production
MRL 9	Low rate production demonstrated; capability in place to begin full rate production
MRL 10	Full rate production demonstrated and lean production practices in place

Figure 13 – Manufacturing readiness level descriptions. Source: "Energy Storage Technology and Cost Characterization" [2]

3.1.12 Technology Readiness Level (MRL)

Technology Readiness Level is a measure used for assessing the phase of development of a technology. Technology Readiness Level indicates how mature the technology is and ranges from a scale of 1 (basic principle observed) through 9 (total system used successfully in project operations). The following illustration, reproduced from the U.S. Department of Energy (DOE) Technology Readiness Assessment Guide (DOE 2011a), shows an overview of each of the scales that the technologies in this report are graded on. All of the technologies included in this report are TRL 5 or higher.



Technology Readiness Level	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or system validation in laboratory environment
TRL 5	Laboratory scale, similar system validation in relevant environment
TRL 6	Engineering/pilot scale; similar (prototypical) system validation in relevant environment
TRL 7	Full scale; similar (prototypical) system demonstrated in relevant environment
TRL 8	Actual system completed and qualified through test and demonstration.
TRL 9	Actual system operated over the full range of expected mission conditions.

Figure 14 – Technology readiness level descriptions. Source: "Energy Storage Technology and Cost Characterization" [2]

3.2 Road-map for battery cost

In this section, a European roadmap for the battery systems developments, costs and economic impacts is proposed, by introducing:

- A cost analysis methodology,
- A current cost analysis for maritime battery applications,
- The evolution of maritime battery costs trend
- Future maritime battery cost target and their possible cost trends,
- The impact on raw material cost.

3.2.1 Cost analysis

Lithium-ion batteries have gained considerable attention due to the high energy/power density, low self-discharge rate, light weight. Lithium-ion battery is currently dominant in the EV market, and stationary applications. This report studies the cost of cell, module, and rack level for different types of batteries.

Figure 1 shows the relationship between battery cells, modules, panels, and full battery pack. It also illustrates the additional components that are required for a complete li-ion BESS.

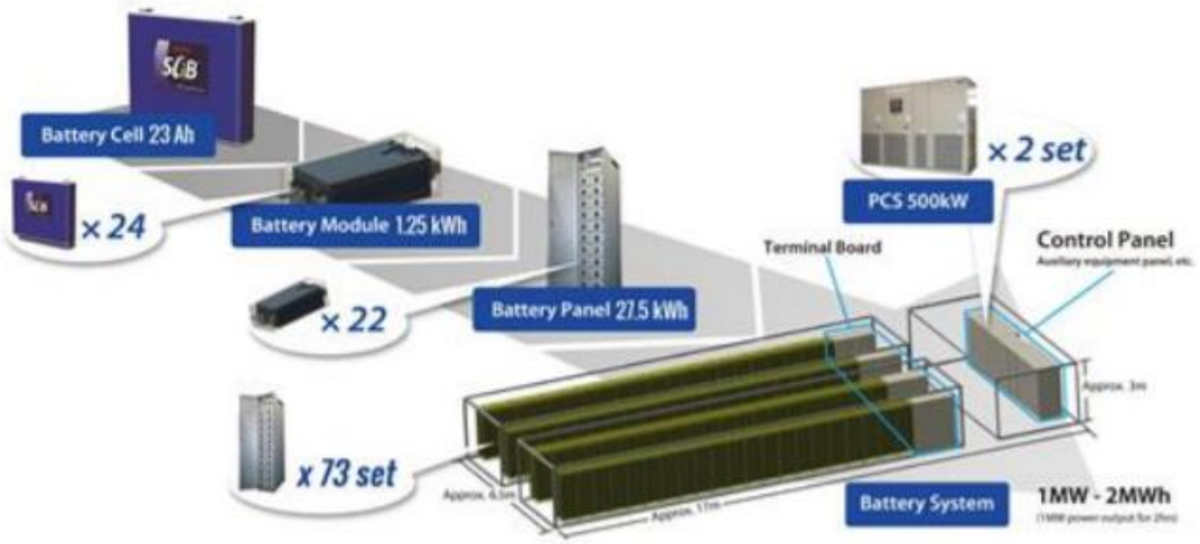


Figure 15 – A schematic view of battery formation[1].

After understanding how a battery is formed from cell level to rack level, the cost breakdown of the cell is represented in the next section of this report. Then, the average cost of batteries based on distinct reliable sources are explained with forecasting of the cost in coming years. In the next step, we introduce different sorts of batteries and show the trend of cost in each battery separately. Moreover, cost breakdown in each type of battery is illustrated. Then, the rack level cost is discussed in the next section of this report.

The goal of this report has already met with prior information. However, it is inevitable to study beyond that because it is needed to investigate which elements are influential in the fluctuation of the cost of LIB, either explicitly or implicitly. Explicitly, the cost of raw materials should be considered a determinant factor in the cost of LIB. On the other hand, history has shown the role of big players in the cost of battery in this industry. Consequently, it is essential to know the big companies and their giant factories at present and their future.

3.2.2 Current cost of batterie for maritime applications

Batteries have a wide price range depending on the application and chemistry. E.g., NCM and LFP batteries are in the range of 410 – 820 €/kWh (per early 2019), LTO is typically double this. In addition, comes power electronics and related efforts towards engineering and installation [14]. Figure 16 presents the Battery cost based on average for marine systems between 100 kWh and 4 MWh[1]. The blue points represent the cost of LFP battery systems, the orange points represent the cost of NMC battery systems, the yellow points represent the cost of LFP battery systems and, the green lines represent the typical cost range of NMC and LFP. As shown in Figure 16 the average cost of LTO is double the NMC/LFP.

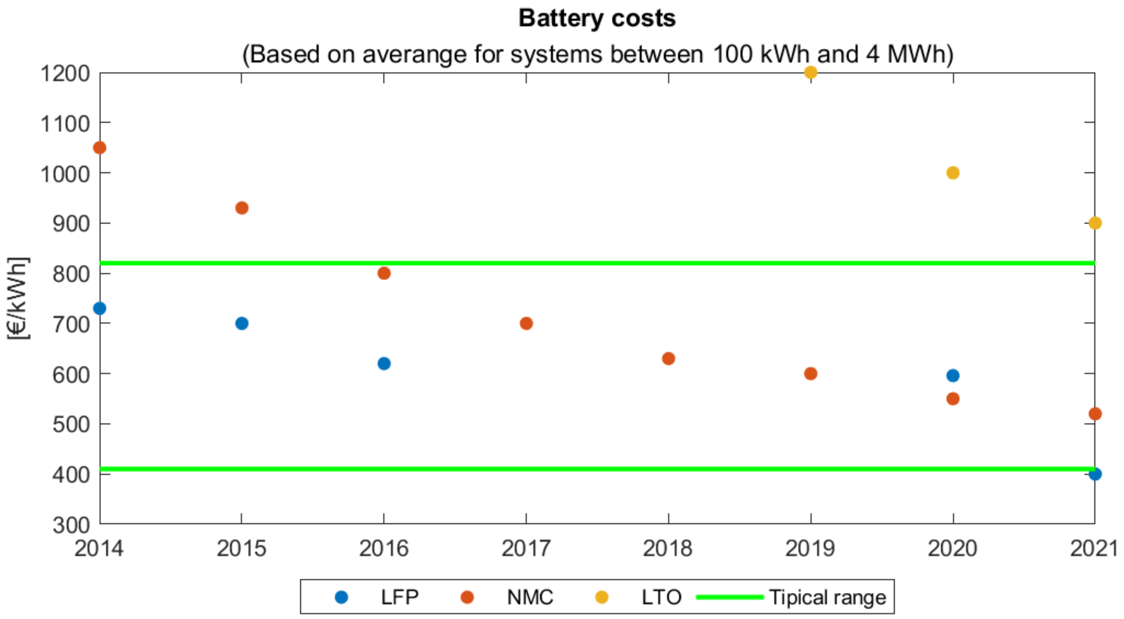


Figure 16 - Battery cost (Based on average for system between 100 kWh and 4 MWh)[2].

A common misunderstanding on battery costs is given by the advertising related to electric cars, which asses a battery cost dropping to 80-165 €/kWh. It is essential to understand that these values are usually related to the cells only, or at least to the modules, for mass-produced cars. Ships require more custom-made systems with higher requirements for the battery, particularly about safety. The "marinization" of the system means that maritime battery systems become significantly more expensive than car batteries [14].

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[1] Data provided by CETENA.

[2] Data provided by CETENA.

The cost of system integration for a battery system is often high and should be considered at an early stage of adoption. Taken the purchase price of the storage system, including power electronics, the total battery cost includes purchase changes, installation at the yard (including electrical), modifications of switchboard, commissioning and testing. The cost of the entire battery system equals the collateral aspects combined.

The lifetime of batteries is highly dependent on the duty cycle for which they are used, relative to the size of the battery. For instance, a smaller battery will have reduced CAPEX, but it will not last as long as a larger battery for a given application. Thus, sizing is a crucial aspect of battery system procurement. The life cycle additionally depends on battery chemistry – there are many different types of lithium-ion batteries – and also varies significantly based on manufacturer or vendor. Systems are most typically engineered and warrantied for ten years of operational life.

Maritime requirements also impact the cost of batteries intended for maritime usage. Compared to batteries intended for customer electronics and electric vehicles, the main cost drivers are related to enhanced safety and performance requirements, more stringent lifetime requirements, and increased system complexity. Installations for ships are commonly customized (when compared to automotive applications) and produced in lower volumes.

Prices of lithium-based cells and systems have significantly been reduced over the last few years. These trends in price reduction continue to surpass market forecasts and are expected to continue in the years to come.

Figure 17 presents the Lithium-ion price forecasts up to 2030. The blue line represents the price of the automotive market, the light blue line and the cyan line represents the previous market predictions and the updated price forecasts for the automotive sector, respectively. The black crosses represent the price of a fully marinized system, the green cross represents the price offered by the market's leader in 2016, and the dotted line represents the expected cost variation range for the marine sector.

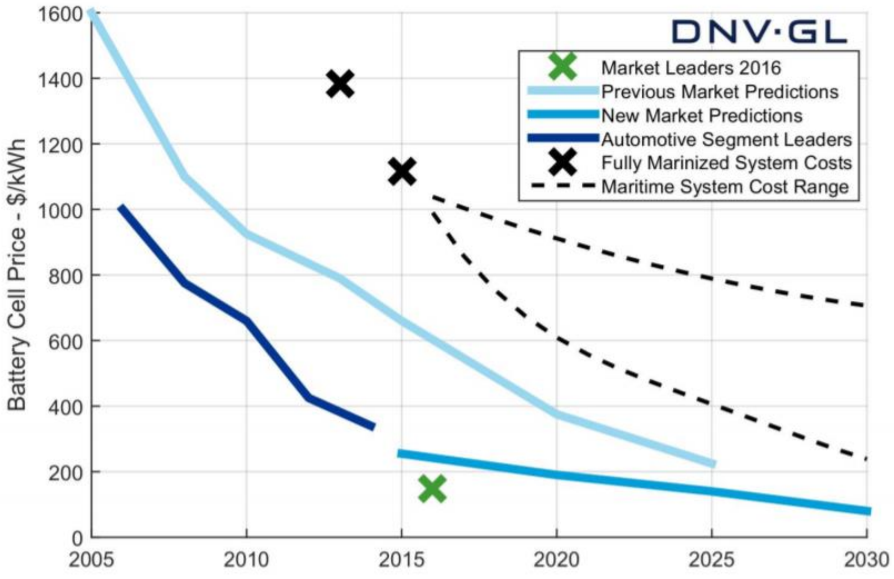


Figure 17 – Previous estimations 2018 Lithium-ion battery price trends [15].

The trends shown in Figure 17 are based on an estimation made in 2018. It is remarkable to notice that these results are comparable to what presented in Figure 16. More precisely, the trends estimated by the Maritime Battery Forum in 2018 are correctly following the current market status, at least for what concerns the LFP and NMC prices, which are in the between of two forecasted trends.

Looking at the Figure 16, the minimum price of a battery system in 2021, based on LFP technology, is of 400 €/kWh which in the current currency are 477 /kWh. The prices seem to have dropped faster than predicted in the Figure 17.

3.2.2.1 Cell cost breakdown

In this section the cost breakdown of a cell with a concentration on the materials is presented in Figure 2.

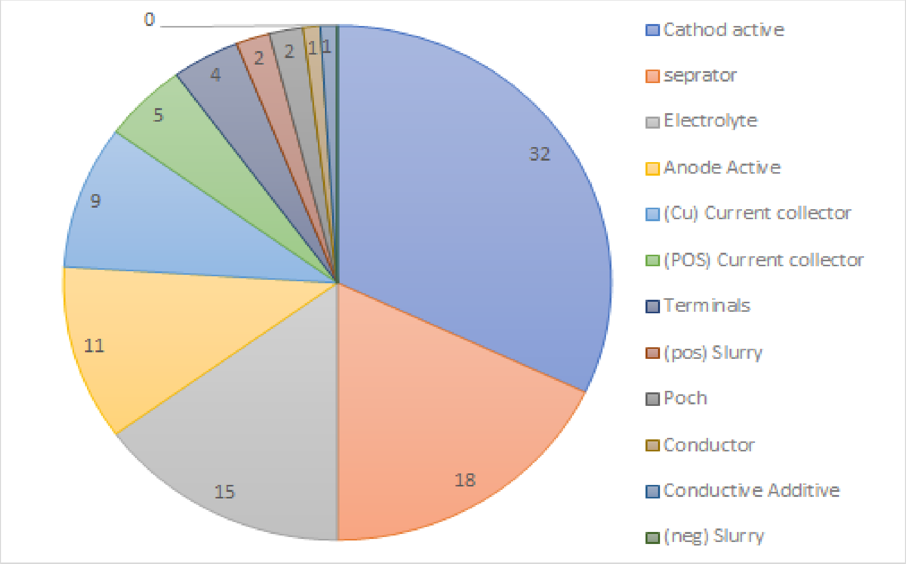


Figure 18 – Average modelled material cost breakdown [2].

As shown in Figure 18, cathode active, separator, electrolyte, anode active accounts for 76% of total cost.

Based on the Bloomberg report [3], the cost of kilowatt-hour for a lithium-ion battery pack according to the one hundred and fifty companies, has reduced to 137$ which is about 12.7 percent per kWh. Based on the report the cost has been decreased a lot, and the future cost would be less than $ 100/kWh. In addition, Duffner et all. [4] Have investigated 21 research based on 17 criteria and all the papers prove that the future cost of lithium-ion battery would be compatible with gasoline engine without governmental subsidy.

3.2.3 Evolution of average cost trend

Figure 19 demonstrates average battery cost including 2 parts. The dark green colour displays the price of cells in 100 kWh based on USD and the light green shows the packing cost for 100 kWh based on USD and total shows the battery cost of 100 kWh.

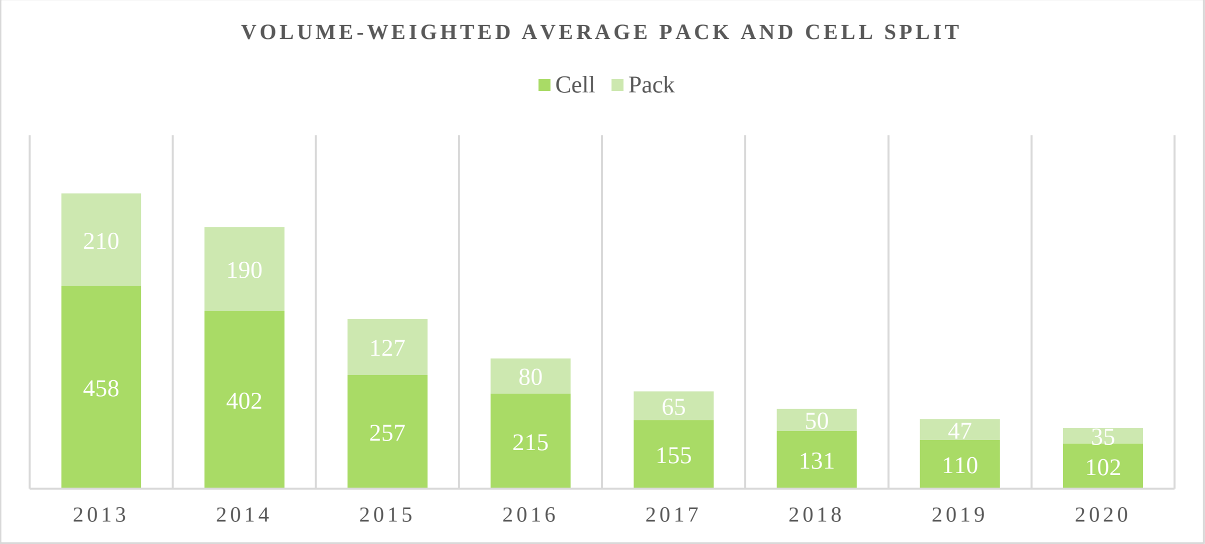


Figure 19 – Average Battery Cost [5].

Moreover, the price of less than $100/kWh has been reported for the first time, which is related to e-buses in china. Considering the volume weighted average, the cost would be about $105/kWh. Averagely battery electric vehicle pack (BEVP) is about $126/kWh based on a volume-weighted average and the cell price is about $100/kWh. Therefore it shows that the pack portion is almost about 20.6% [5]. The variety of chemistry applied in battery market leads to different variety of cost. Battery manufactures compete to mass production for batteries with higher energy density with some new components such as NMC (9.5.5), NMCA. In addition, LFP plays an important key role because of its price which was reported the lowest price which is $80/kWh. The aforementioned cost of battery pack is average of battery pack cost and in different applications it might be varied. For instance, two different types of battery applications which are HEV, and PHEV are shown and compared in terms of cost breakdown in figure 4. Therefore, it is important to study cost of distinct types of batteries. Further in this report we study the most important batteries in LIB field.

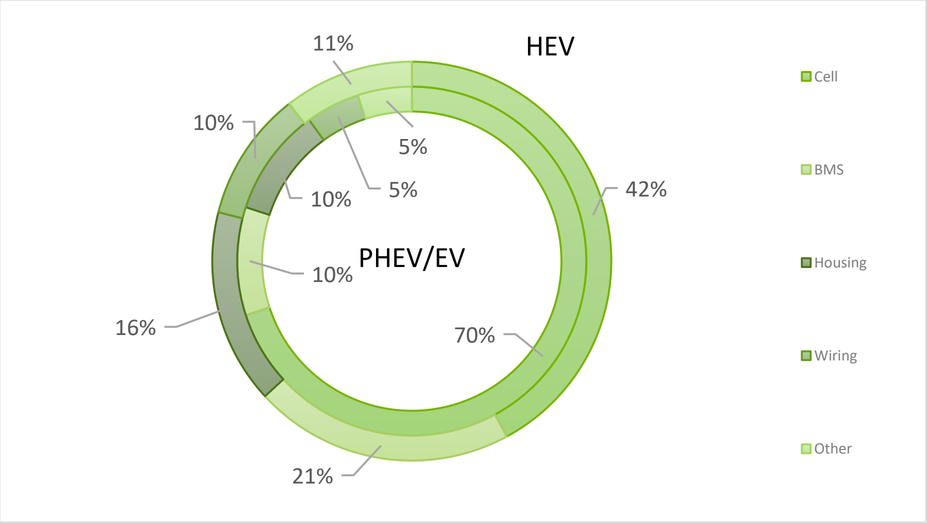


Figure 20 – Comparison of HEV and PHEV battery cost breakdown[6] .

3.2.4 Battery costs target for marine batteries

To determine the cost target for marine batteries there are variables to take into account: the costs for fuel and for electricity at the area of operations. With these two variables it can be determined what the costs per cycle of a battery should be to achieve a lower costs compared to sailing on diesel. The difference in costs for maintenance or the initial costs for installing diesel propulsion or electric propulsion is however not taken into account in this calculation.

3.2.4.1 Diesel energy costs

The costs for the energy from diesel is calculated by assuming a specific fuel consumption of the engine of 200 g/kWh. This results in approximately 5000 kWh of energy which is available for propulsion from 1 ton of marine fuel. Additionally the maintenance costs in diesel propulsion is responsible for a significant part of the TCO. Based on a feasibility study for zero emission propulsion the maintenance costs for marine diesel propulsion is estimated at approximately 0.05 €/kWh.(Reference to: TNO 2019 R10453 Feasibility study for a zero emission, hydrogen fuel cell powertrain for the Gouwenaar II) The costs for energy from diesel is then calculated by dividing the fuel price, combined with the maintenance costs for producing 5000 kWh, by 5000, resulting in the energy costs in €/kWh. The efficiency of a diesel direct propulsion train is assumed to be 97% in this case.

$$Diesel\ energy\ costs = \frac{Fuel\ price\left[\frac{€}{ton}\right] + maintenance\ costs\ 250\ [\frac{€}{5000kWh}]}{5000\ \left[\frac{kWh}{ton}\right]} / \ 0.97\ = [\frac{€}{kWh}]$$

3.2.4.2 Battery energy costs

The costs for energy from the battery consist of the costs for the cycling of the batteries and the costs for the electricity at the area of operations. The cycling costs of the battery are calculated by the system costs, which are indicated in Euro per kWh, divided by the number of cycles the battery can perform until the end of life of the battery. Both the cycling costs and the electricity costs are expressed in Euro/kWh. For electric propulsion an efficiency of 90% is assumed.

$$Battery\ energy\ costs = \frac{Cycle\ costs\ \left[\frac{€}{kWh}\right] + Electricity\ price\ \left[\frac{€}{kWh}\right]}{0.9\ (efficiency)} = [\frac{€}{kWh}]$$

3.2.4.3 Battery cost target

The cost target for batteries can be calculated by comparing the diesel price and electricity price. By rewriting the equations above the required cycle costs can be calculated for any specific combination of diesel price and electricity price.

$$Cycle\ costs = \frac{Fuel\ price\left[\frac{€}{ton}\right] + 250}{5388.889} - Electricity\ price[\frac{€}{kWh}] = [\frac{€}{kWh}]$$

As an example, at a diesel price of 500 €/ton and an electricity price of 0.10 €/kWh the required cycle costs of the battery should be:

$$((500 + 250)/5388.889) - 0.1 = 0.039\ [\frac{€}{kWh}]$$

If a battery can perform 5000 cycles at a specific design condition, this results in a system costs of 196 €/kWh for which the battery system should be installed on board of the vessel. A battery system costs below 196 €/kWh would be needed for a cost benefit for battery powered propulsion compared to diesel power propulsion. The number of cycles that the battery system will perform during its design life is an important factor for determining this cost target. Therefore, three different scenarios are shown in the tables below. Each scenario shows the battery cost target in system costs [€/kWh] depending on fuel price and electricity price for 3000, 6000 and 10000 cycles, as proposed from Table 1 to Table 3.

Table 1 – Battery cost target, 3000 cycles

Battery cost target (system costs) [€/kWh]					
3000 cycles		**Electricity price [€/kWh]**			
		0.01	**0.05**	**0.10**	**0.15**
Fuel price [€/ton]	**300**	276	156	6	-144
	400	332	212	62	-88
	500	388	268	118	-32
	600	443	323	173	23
	700	499	379	229	79
	800	555	435	285	135
	900	610	490	340	190
	1000	666	546	396	246

Table 2 – Battery cost target, 6000 cycles

Battery cost target (system costs) [€/kWh]					
6000 cycles		**Electricity price [€/kWh]**			
		0.01	**0.05**	**0.1**	**0.15**
Fuel price [€/ton]	**300**	552	312	12	-288
	400	664	424	124	-176
	500	775	535	235	-65
	600	886	646	346	46
	700	998	758	458	158
	800	1109	869	569	269
	900	1220	980	680	380
	1000	1332	1092	792	492

Table 3 – Battery cost target, 10000 cycles

Battery cost target (system costs) [€/kWh]					
10000 cycles		**Electricity price [€/kWh]**			
		0.01	**0.05**	**0.1**	**0.15**
Fuel price [€/ton]	**300**	921	521	21	-479
	400	1106	706	206	-294
	500	1292	892	392	-108
	600	1477	1077	577	77
	700	1663	1263	763	263
	800	1848	1448	948	448
	900	2034	1634	1134	634
	1000	2220	1820	1320	820

3.2.4.4 battery cycle costs target

Projecting this on the current situation results in the figure below. The current marine fuel oil price is assumed to be approximately 500 €/ton. The cycle costs for the battery systems currently on the marine market range from 0.045 €/kWh to 0.33 €/kWh.

In the figure below you may see 4 different scenarios for different electricity prices of 0.01 €/kWh, 0.05 €/kWh, 0.10 €/kWh and 0.15 €/kWh.

As can be seen, the batteries with the lowest cycle costs of 0.045 €/kWh would require an electricity price just below 0.10 €/kWh to achieve a lower cost for energy compared to a diesel powered vessel, at the assumed fuel price of 500 €/ton.

It also indicates that with the current marine battery system costs and fuel prices even an electricity price of 0.01 €/kWh would not be enough to make batteries the cheaper option.

On the abscissa axis there is the target cost per cycle associated with the 4 different electricity costs, we can see how this target cost is higher with a lower electricity price. Another factor that influences this target is the price of fuel oil, a higher fuel price helps to maintain a higher target cost per cycle of the batteries. A higher target cost per cycle makes the use of batteries in water transport more economical.

The most effective way of making batteries the more cost efficient option would be to reduce the electricity costs and to increase the fuel costs, as shown in Figure 21 below.

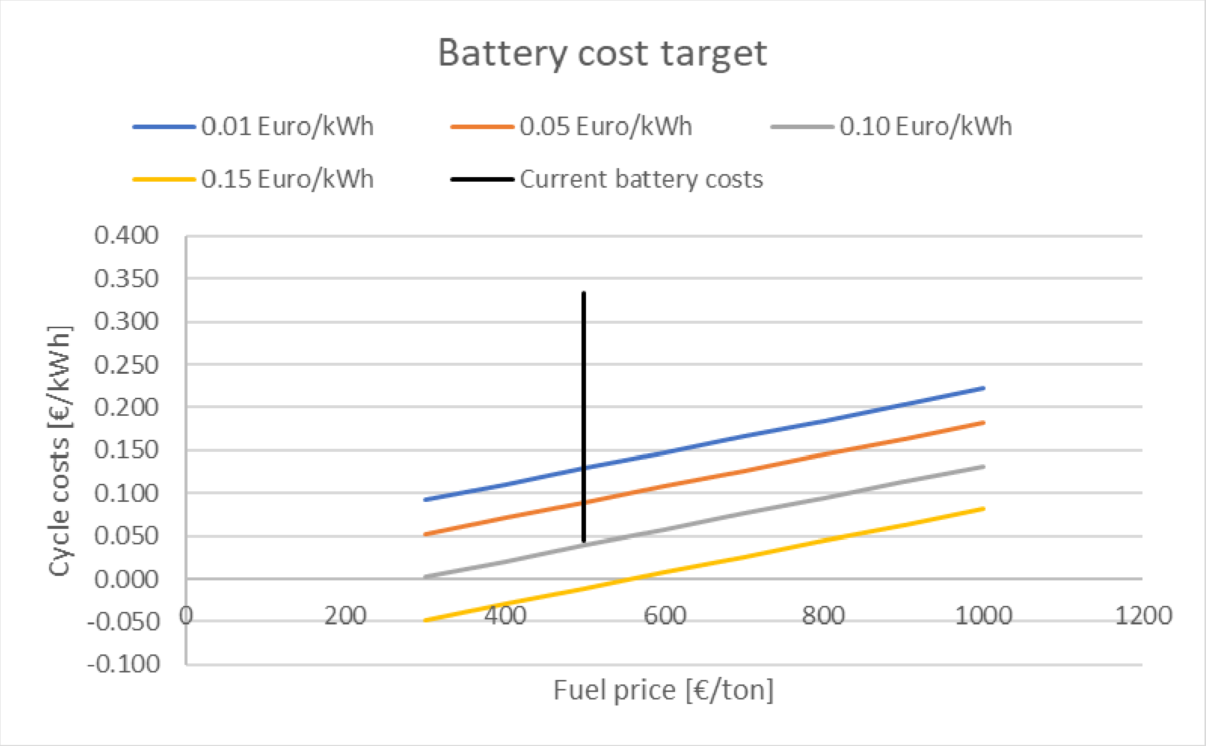


Figure 21 – Battery cost target depending on the fuel price

3.2.5 Future average cost trend

As mentioned before, the battery price would be less than $101/kWh by 2023 [5] and might be less than $73/kWh by 2030 (Figure 22). IHS Markit believes that the result of technology and improvement lead to decrease the cost of ion batteries as much as possible. Finally, the two key players which are transportation and electric grid storage are looking forward to reducing the cost of batteries in compassion with combustion engines and power generations.

Moreover, following research [5], [7] notified that the cost of the battery would be less than $58/kWh by 2030. Even though it seems audacious, applying the solid-state batteries is one of the solutions. These kinds of batteries might be cheaper more than 40% in mass production in comparison with the contemporary batteries.

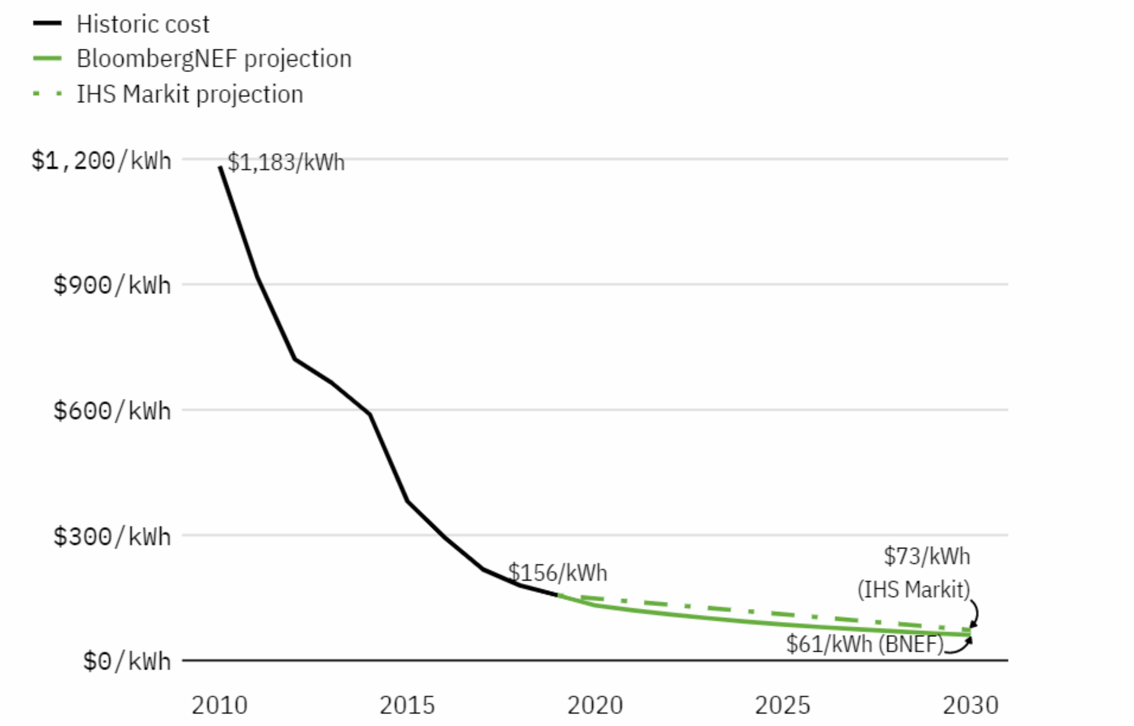


Figure 22 – Prediction of sales price of battery [8]

For instance, Tesla has asserted that it has been so successful in the battery cost reduction and the company would make an electric car which is only $25.000 dollars by 2023. The CEO of Tesla believes that new cell designs for anode and cathode components, and cell assimilation leads to reduction of battery cost about 56% in 2023. LFP which is mostly produced by BYD and CATL has the goal to below $100/kWh based on the IHS Markit. In addition, NMC and NCA have the same target to have a price less than $100/kWh by 2024.

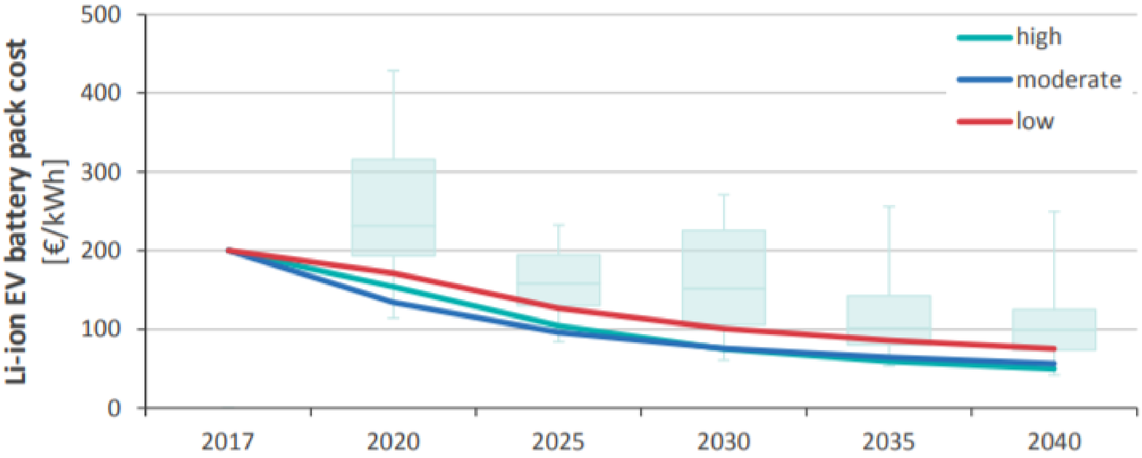


Figure 23 – Cost-development of Li-ion battery packs for EVs over time based on three different deployment scenarios [9].

Another research by [9], predicted the average cost of LIB in three scenarios. Their forecast shows a 50% reduction by 2030 and 63 to 75 % by 2040, in comparison with the current situation. Low moderate scenario represents EV battery prediction. Moderate and high scenarios present energy-designed stationary storage and power-designed stationary storage, respectively which is shown in figure 6.

3.2.6 Diversity of batteries

There are different types of LIB in the market in which a couple of them have attracted more attention due to their specifications, and characterization. In this report a special focus has given to NMC, LFP, LTO, and NCA. A Key performance graph in Figure 24 compares their characterizations.

3.2.6.1 Cost trend analysis

Irena 2017 has considered three scenarios which are worst, reference and best cost in 2030. The following diagram, figure 8, the future of cost batteries for these different types of batteries are demonstrated and compared with each other in 2016 and 2030 [10].

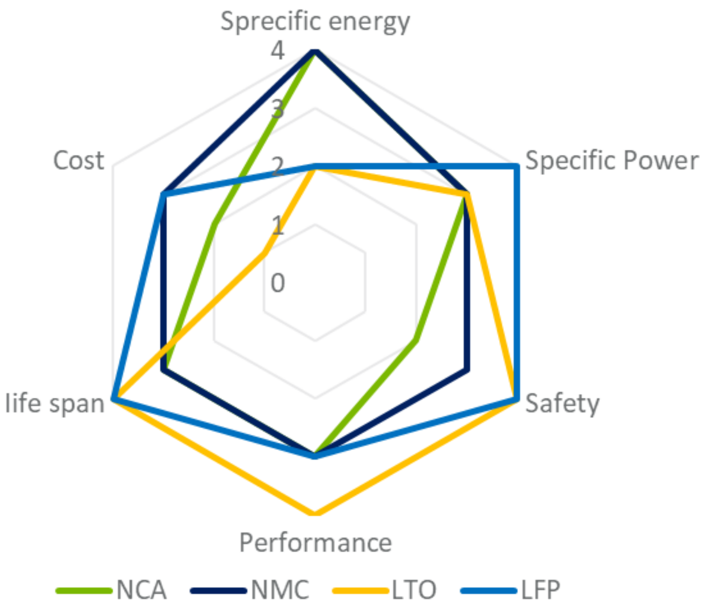


Figure 24 – Key performance of batteries

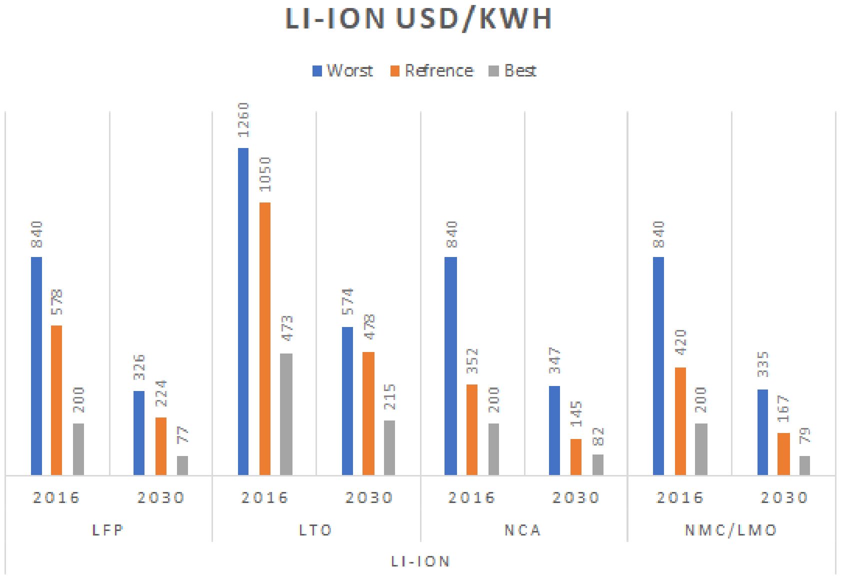


Figure 25 – Cost trend analysis in 4 types of LIBs [10].

3.2.6.1.1 Graphite-based anode batteries cost breakdown

Please note that this study, considers batteries with two perspectives: graphite-based anode and LTO-based anode. A research by [11], studied the total material costs of 10 different cell chemistries in combined cathode active material cost, anode cost, and secondary material costs that is illustrated in figure 9. In this figure different types of NMC, NCA, and LFP are compared in terms of their materials.

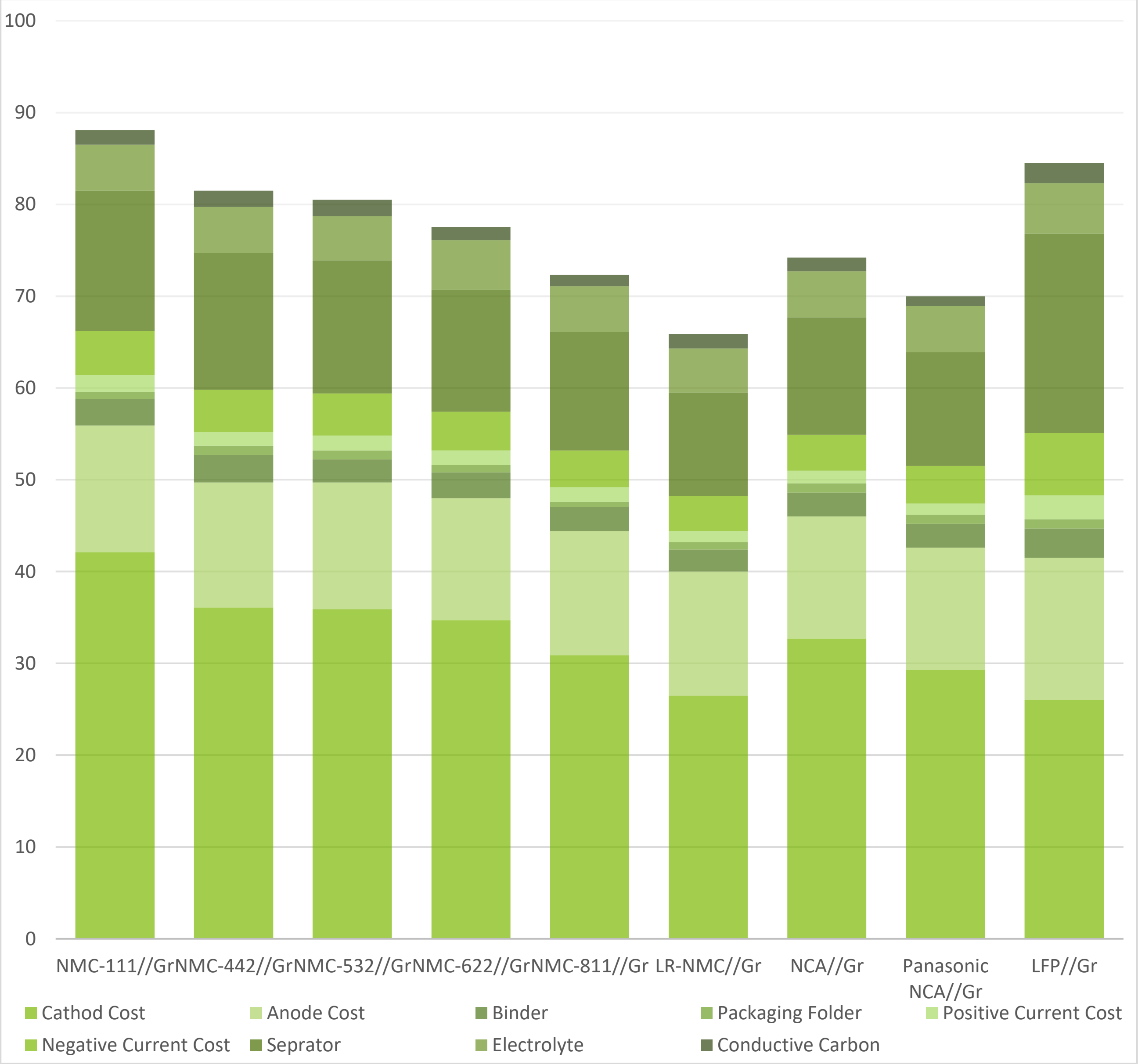


Figure 26 – Cost breakdown of distinct sort of batteries [11].

In this part we want to go in-depth and study one specific graphite-based anode battery which is NMC-622. The cost breakdown and cost trend of this battery are presented.

Figure 10 shows cost breakdown of a battery with a special focus on the anode composition of an NMC-622 battery. Material cost represents 60-80% of the total cost in which two most costly components are cathode and anode [7].

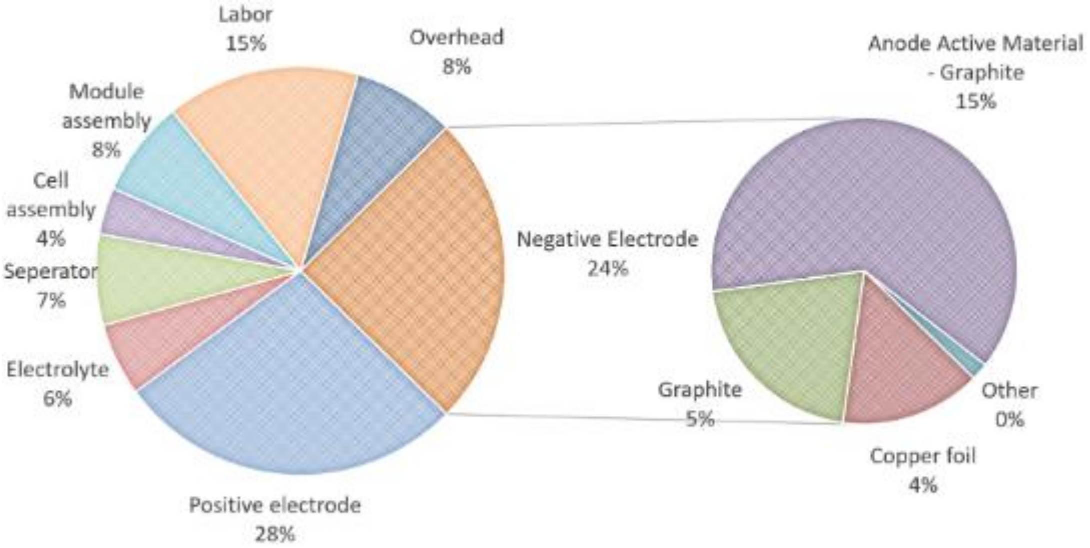


Figure 27 – Cost breakdown of the NMC-622 Graphite Anode battery with a special focus on the anode composition [7] .

Figure 28displays the prediction of sales cost of NMC-622 battery based on battery cost breakdown.

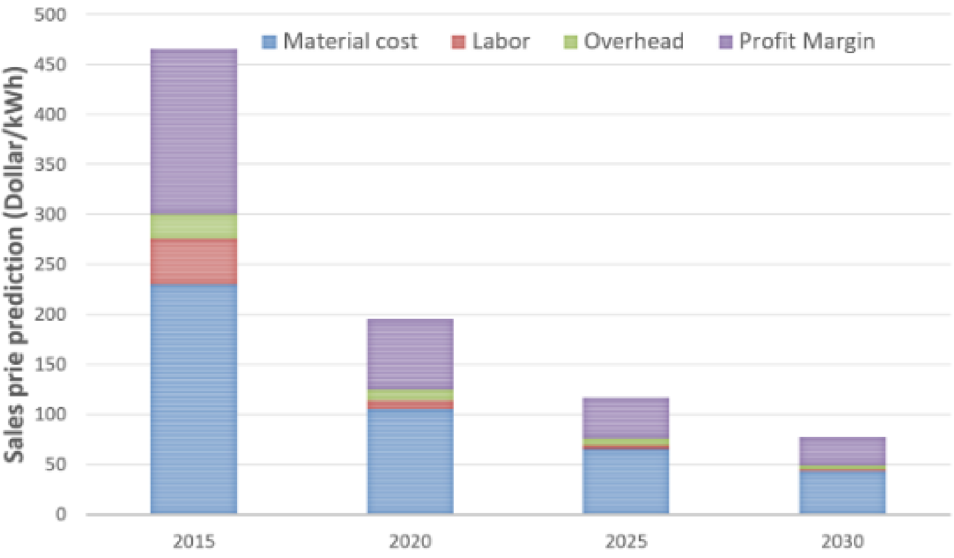


Figure 28 – Prediction of sales price of the NMC-622 Graphite Anode battery [7].

3.2.6.1.2 LTO-based anode batteries

There are 2 types of famous anode batteries; graphite-based, and LTO-based. Here we go through to compare LTO-based batteries with graphite-based. Nowadays graphite-based are more widespread due to their cost but LTO-based batteries are more efficient as it is shown figure 12.

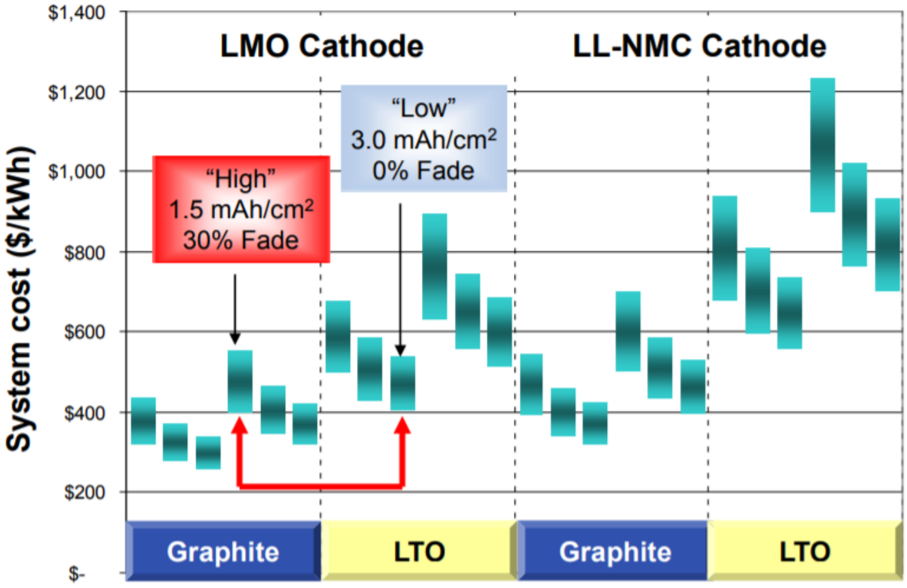


Figure 29 – Cells employing LTO anode are significantly more expensive than graphite anode packs, with the "low" cost LTO cell designs comparable in price to "high" cost graphite designs [12].

Figure 13 shows the cost comparison of LTO-based batteries and graphite-based batteries. The graph clearly shows how costly LTO-based are in comparison with graphite-based batteries.

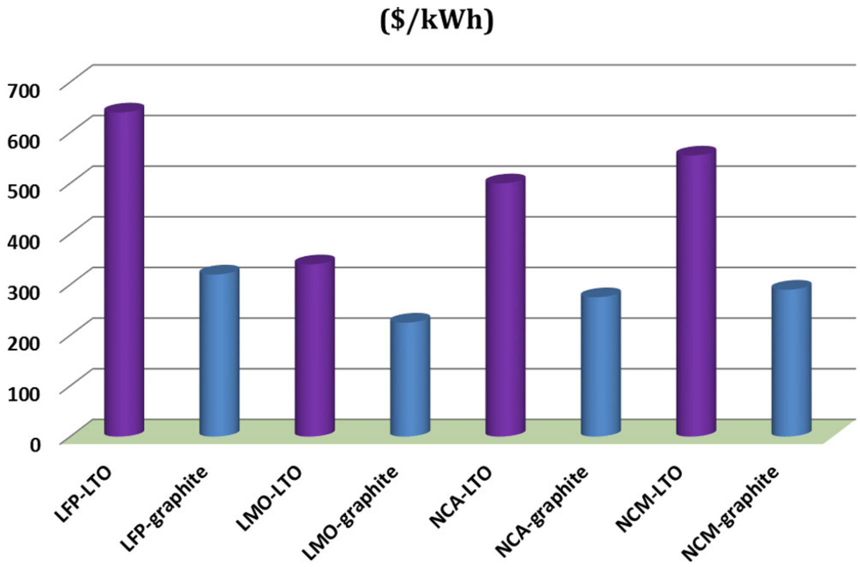


Figure 30 – Comparison of the cost on typical LTO-based LIBs and their graphite-based counterparts [12].

3.2.6.2 Rack level

The Cost of BESS is determined with two solutions:

Cost per kW (MW): this cost is considered the installation cost over swift output of power rating system and determined as $/kW-AC or $/kW-DC.

Cost per kWh (MWh): The total price of the system over the estimated output and the proper unit is $/kWh-AC or $/kWh-DC. In addition, it should determine that it is based on the applicable storage capacity considering the rated storage capacity regarding they are not the same.

Moreover, for all BESS, the cost is determined as follows:

Installation cost: the price of equipment, BOS cost, and EPC.

Levelized cost: the total designing, construction, applying BESS for the complete period. In addition, the maintenance cost, battery degradation should be considered for decreased output. When a BESS is compared with an alternative resource, the LCOS can be regarded.

The following picture shows the cost break down structure of a BESS.

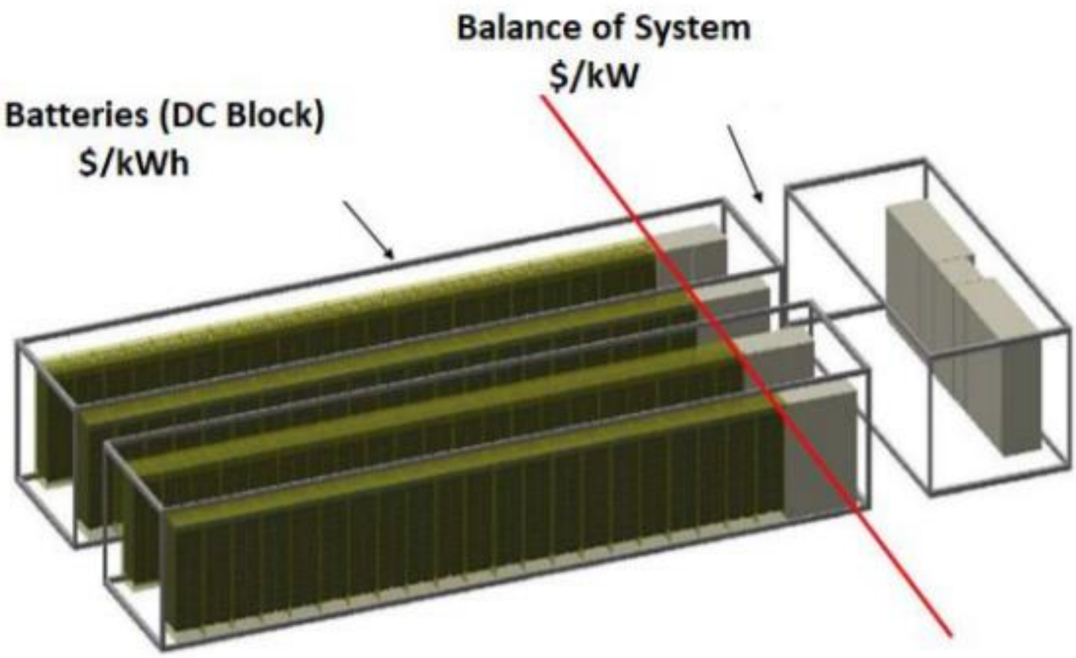


Figure 31 – BESS components[1].

Figure 15 tries to explain the concept of BESS by applying a water tank as an example. The volume of the tank is like energy (kWh), and the flow rate (gallons/hour) is similar to power (kW).

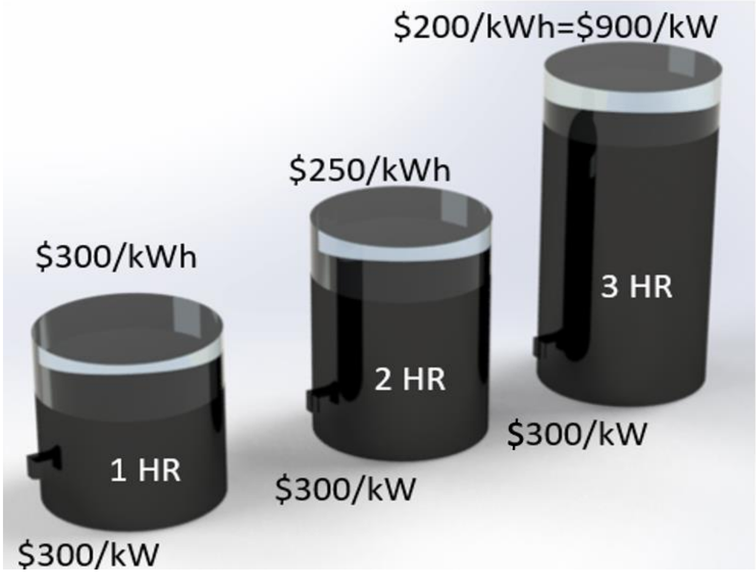


Figure 32 – BESS cost analogy.

As figure 15 shows a 3-hour $200/kWh battery with BOS estimated totally $300/kw. If all the costs are converted to kW, the 3 hour $200/kWh battery is $600/kW. Add the cost of BOS component give us the total cost of BESS which is $900/kW.

Figure 16 and 17 illustrate li-ion battery systems and shows all the parts in the vertical bar (it is to be highlighted that maritime battery system costs are higher than those proposed here, mainly due to their marinization). The graphs show the rapid reduction of price from 2012 to 2025. The estimated cost for a BESS declines to $40/kWh or in other words it is just 15 percent of the total cost.

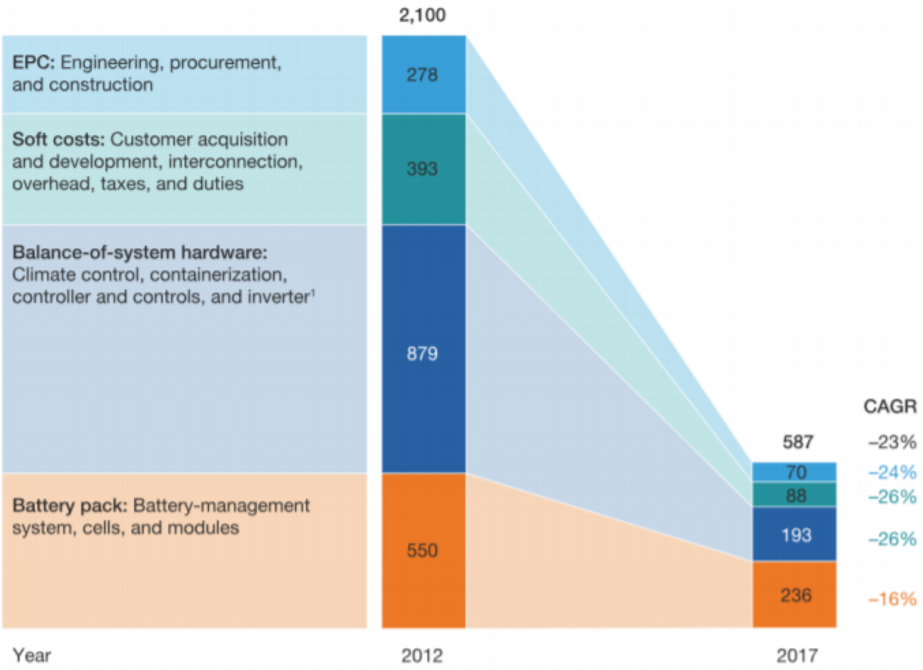


Figure 33 – Cost breakdown of 1 MW BESS (2017 &/KWH) [13].

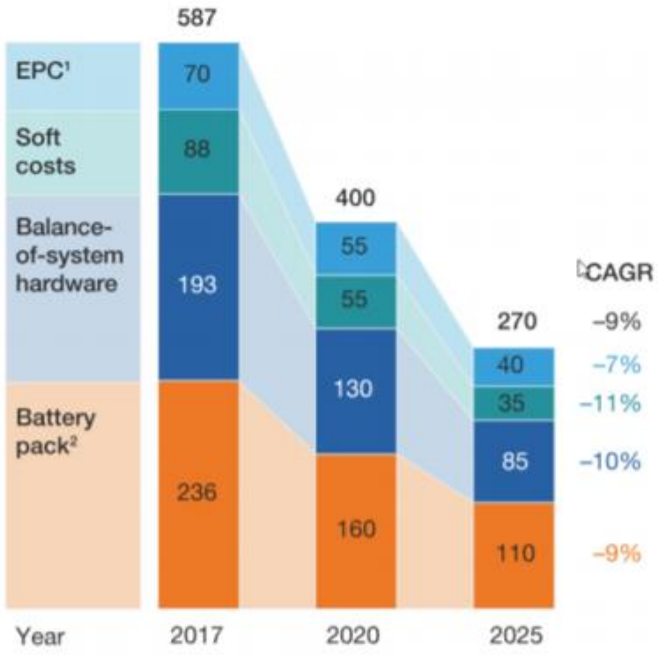


Figure 34 – Projected decline in component costs for a 1 MWH BESS (2017 $/KWH). [13].

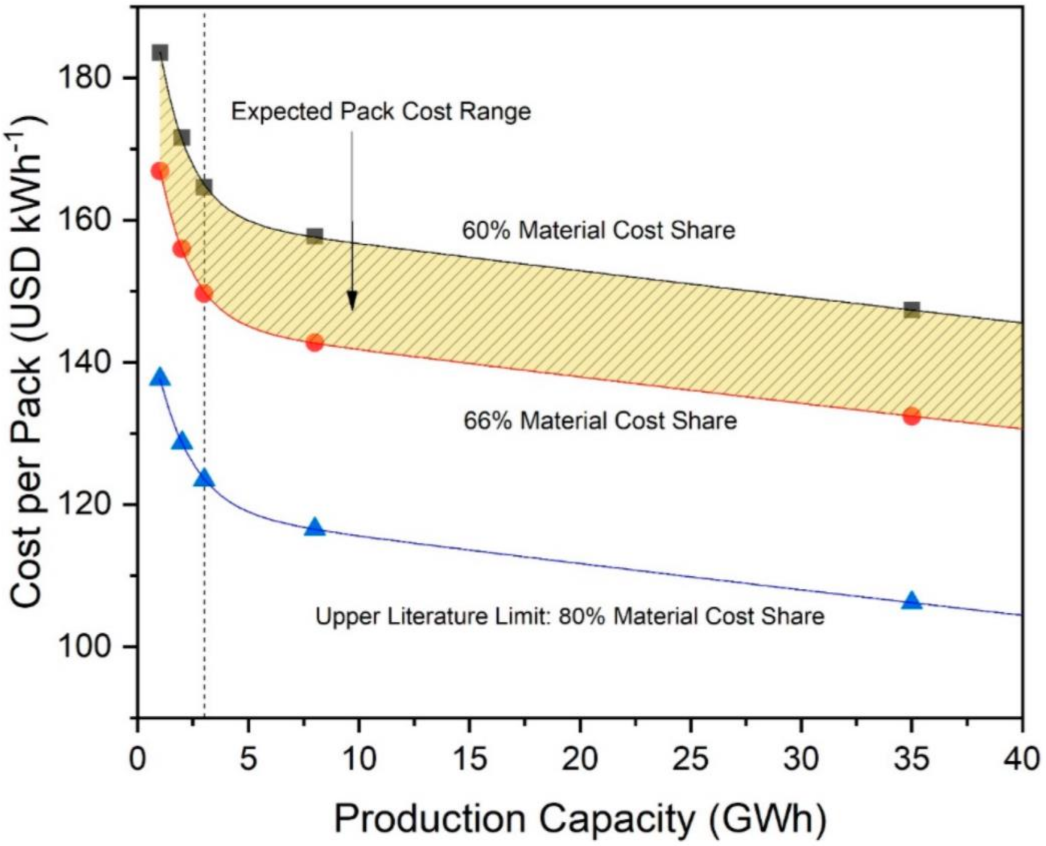


Figure 35 – Cost per battery pack for batteries based on NCA//Gr cell chemistry as a function of factory production capacity, with curves representing 60, 66, and 80% share, respectively, material cost.

Figure 18 displays the cost of rack pack of NCA- Gr with cell material cost shares between 60 and 80%. 60, 66, and 80 are chosen based on prior studies and we see three scenarios for these three-material cost. Dotted line indicates 3 GWh, the point at which process-based economy of scale effects reach their maximum.[11].

3.2.6.3 Share of battery types in BESS

In the last decade BESS has applied NMC batteries, and in the last two years the demand for NMC has grown rapidly which leads to outstrip the current supply. Because the demand for NMC grows every day and the price has been remained flat, LFP suppliers has penetrated to the NMC-constrained territory with competitive cost. Therefore, LFP has become an attractive solution for all applications and it would change the battery games by 2030 which is shown in figure 19.

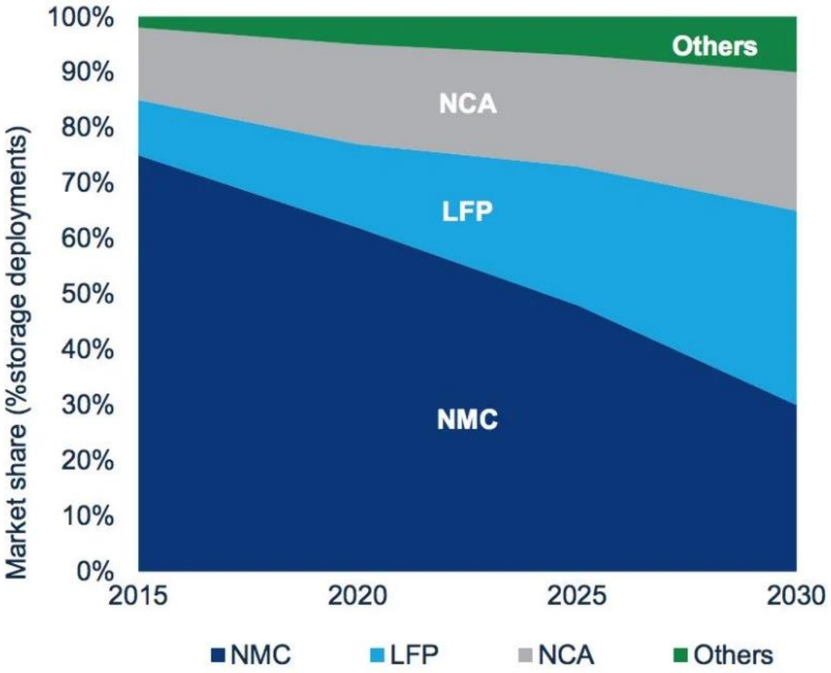


Figure 36 – ESS battery chemistry market share forecast [14]

3.2.7 Impact of raw material cost

Raw material should be considered as an influential factor on cost fluctuation through time. Figure 20 shows raw material of some types of batteries. Figure 21 shows how different batteries are influenced by the changing price of Cobalt. Cobalt is known as one of the popular and expensive raw material in LIBs. As it is expected the all cobalt-containing LIBs are affected by cobalt price change.

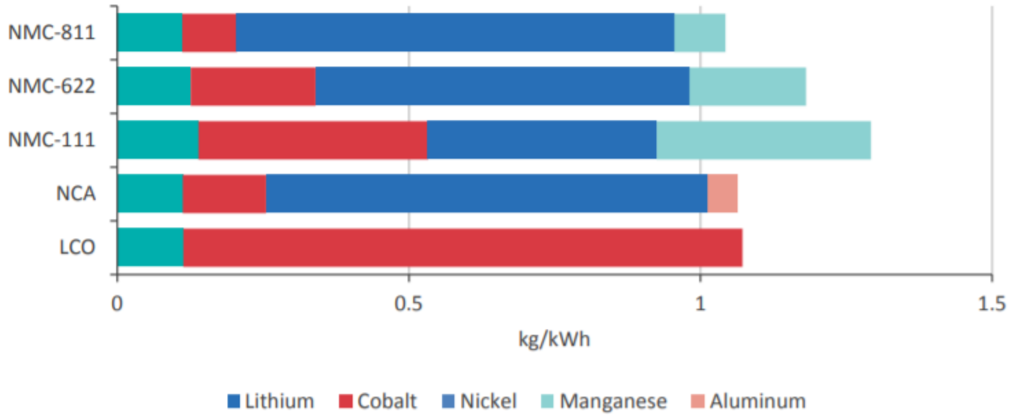


Figure 37 – Element requirement for Li-ion battery cathodes

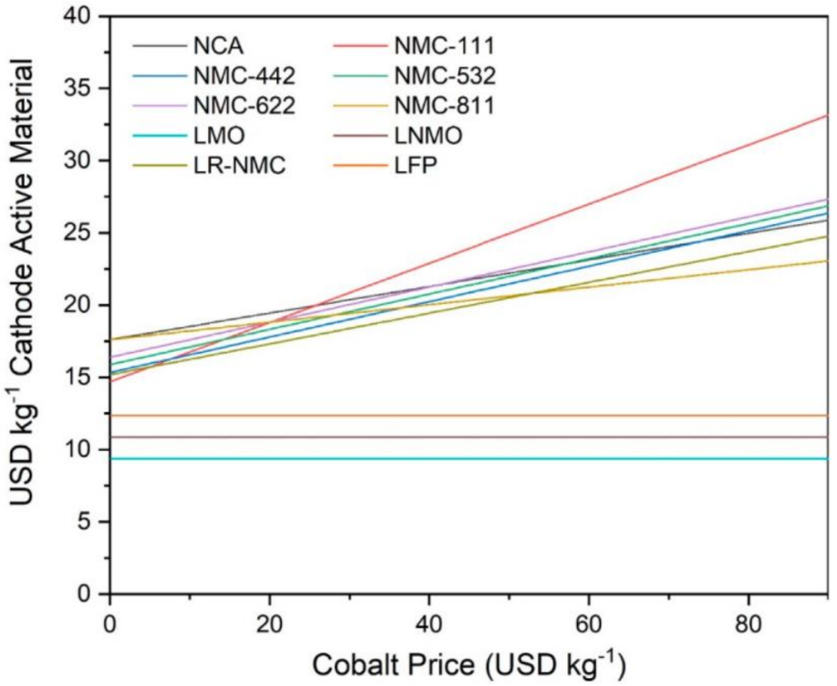


Figure 38 – Sensitivity of total manufacturing costs of NCA, NMC-111, NMC-442, NMC-532, NMC-622, NMC-811, LMO, LNMO, LR-NMC, and LFP cathode active materials to market price of cobalt from theoretical range of 0 USD kg−1 to 90 USD kg−1 as determined by battery cell and cost model. [11].

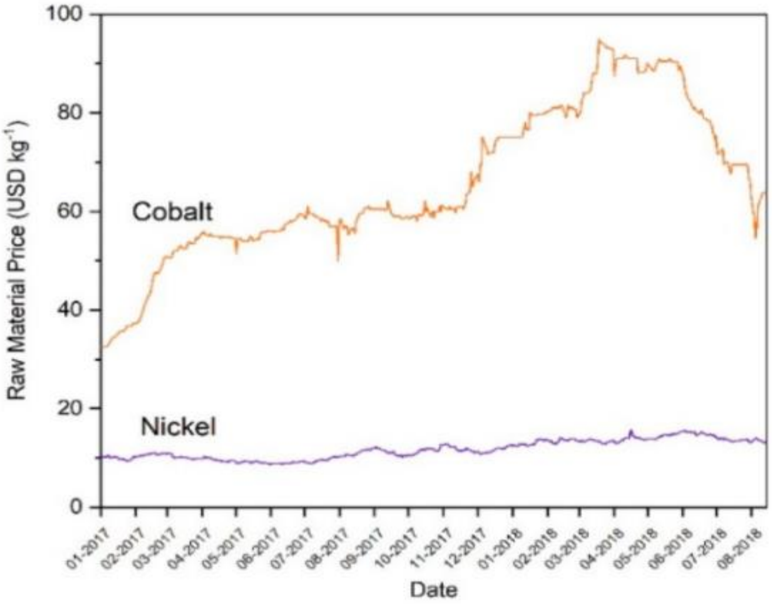


Figure 39 – prices of raw cobalt and nickel metal from 01-2017 to 03-2018 [11].

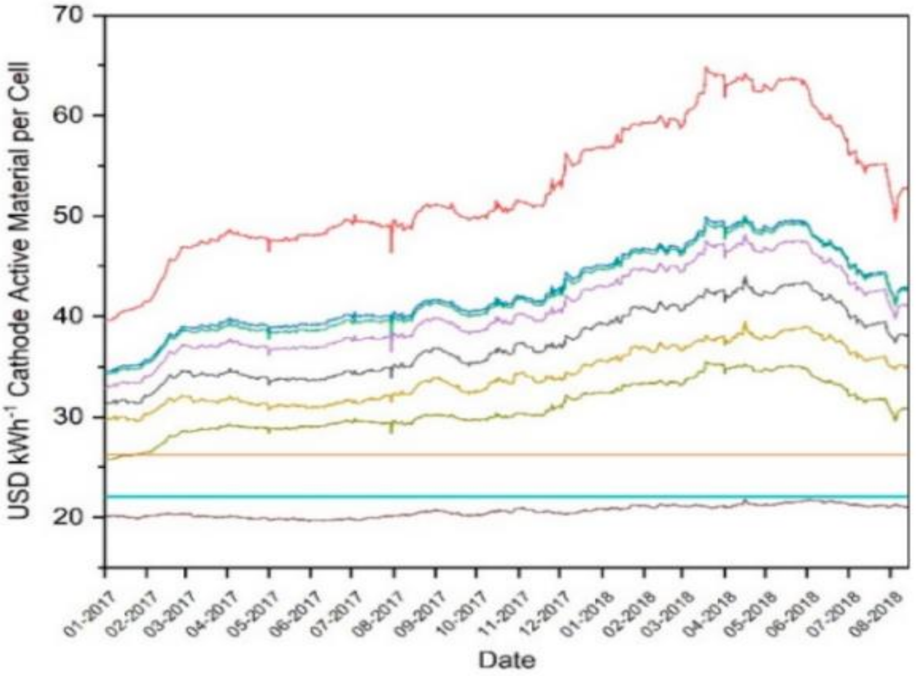


Figure 40 – sensitivity of total LIB manufacturing costs during this same time window as determined for NMC-111 (red), NMC-442 (blue), NMC-532 (green), NMC-622 (purple), NMC-811 (yellow), NCA (black), LMO (turquoise), LNMO (brown), LR-NMC (olive), and LFP (orange) [11].

Figure 22 illustrates the price of cobalt and nickel from 2017 to middle of 2018 in which the price of cobalt is increasing despite of last 6 years. This immediate fluctuate shows that the price trend is not always decreasing or stable. Figure 23 shows the sensitivity of different types of LIB based on fluctuation of cobalt.

WoodMac [15] asserted that with insisting on decreasing CO2 emissions there might be resource limitation sooner than expectation. It was mentioned in their research that there are two scenarios for this issue. In the first scenario which it considers the limitation of global warming by 2.5 degrees, Electric vehicles contains 20% share of vehicle sales and it would reach to more than 50 percent by 2035 which is illustrated in figure 24. This scenario will lead to mass consumption of cobalt that will be doubled by 2025 and batteries need more than 30% of global demand by 2030 which is only 5% nowadays. Even though the results are different, but the same solutions are concluded: increasing supply and decreasing demand. For a drastic change to a successful transition, all the aspects such as supports from NGOs, governments, the procedure of mining and even the supply chain should be improved. For instance, Tesla has announced that the company has discovered a lithium deposit located near the U.S.A Gigafactory and they have invented a new method in terms of extracting lithium and extracting it by the end of 2020.

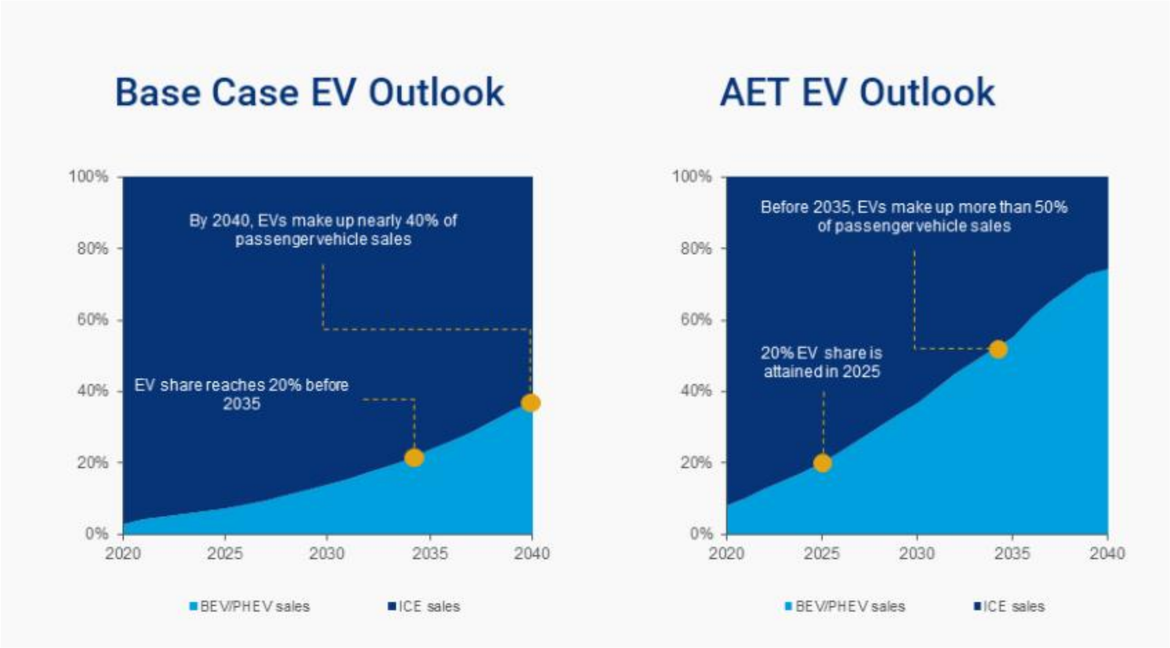


Figure 41 – Comparing two scenarios of forecasting[15].

3.2.8 Cost gap and future cost evolution of battery cells

This section aims to show why although the price of lithium-ion batteries has declined in EV especially in the automobile industry, the price of lithium-ion batteries in the marine industry hasn’t influenced that much.

he following Figure 42 shows the price trend of lithium-ion batteries from 2010 till 2030 in the automobile industry.

On the other hand, Figure 43 illustrates the price development and forecast of lithium-ion batteries in the maritime application including the prediction of a leader company Leclanché in this area.

Three reasons have been driving down battery costs, summarized in Figure 44.

First, the technology within the battery has improved. Second, manufacturers have figured out how to build batteries more efficiently. Third, government policies and its support of green EV. (LEE, 2020; Paul Caine, 2020).

3.2.8.1 Cost gap

Technological improvements play a role in driving down battery costs. Through the last decade, it turned out that the term lithium-ion battery is an umbrella term for several distinct battery chemistries. Over time, scientists have produced new batteries that deliver more and more energy per kilogram. This not only decreases the cost of the chemically active parts of the battery but also shows that batteries can be physically smaller and lighter for a given power budget, which lowers the per-kWh cost of every other component. As there hasn't been that much research on the marine application this area should be improved and developed.

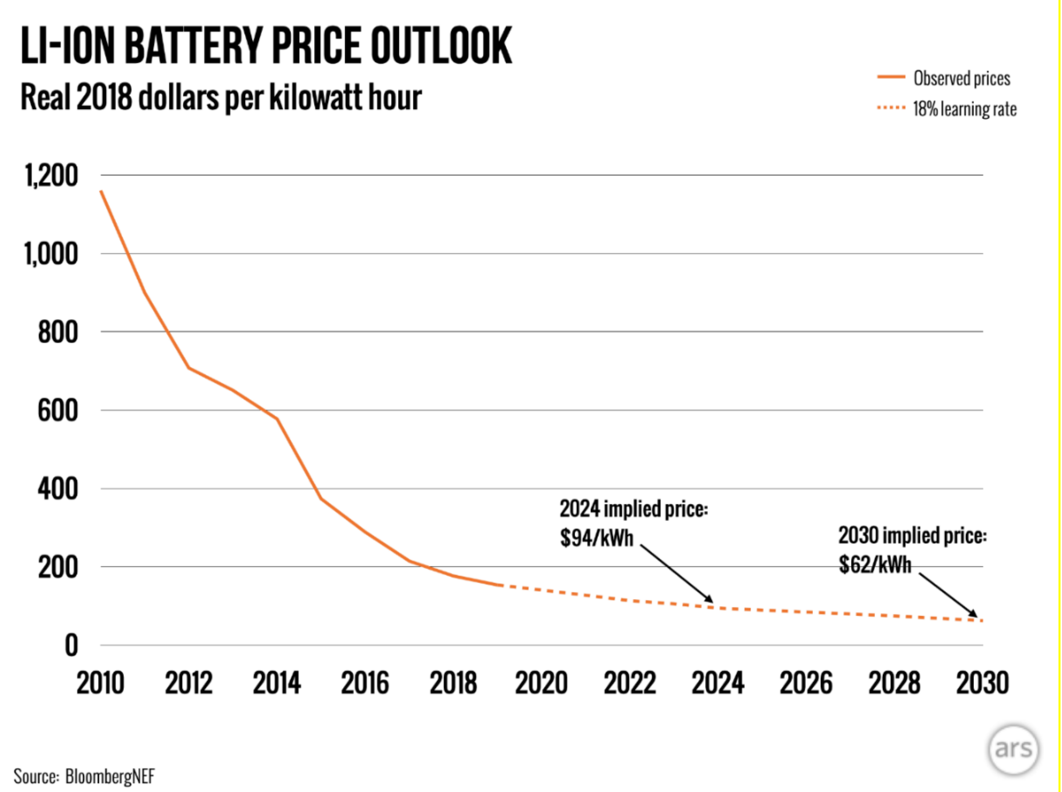


Figure 42 – price trend of lithium-ion batteries in electric cars (LEE, 2020).

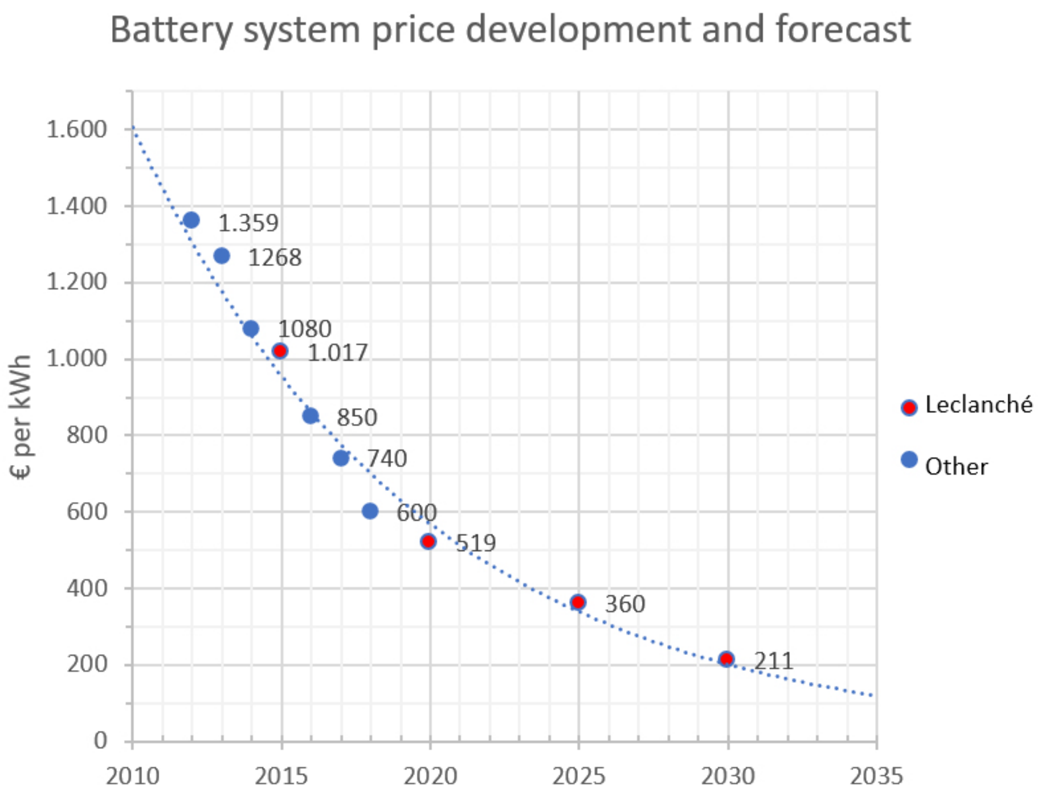


Figure 43 – Compilation of battery pack price development data for maritime application gathered by Marstal Navigations Skole combined with estimates and realized prices from Leclanché (European Union, 2020).

3.2.8.2 *The role of manufacturers*

The role of big players in the reduction of batteries has been critical. Most notably, Tesla Has been a pioneer in this area. Tesla tried to popularize the battery-electric car concept, but Tesla has been a battery company as much as it is a car company. The emergence of a company or a couple of companies could play an equal role in the marine battery industry. This industry needs some companies that could bring new technology.

Tesla was founded in 2003 and its efforts after 20 years are tangible. Therefore, it seems there is a lack of such a big player in marine battery production to influence the market.

At the same time, the market was growing due to the necessity of lithium-ion batteries in laptops and cell phones. The companies invested millions of dollars into research and development to make batteries more efficient and cheaper. Although the market of laptops and cell phones has gained much attention, its market has not been comparable to the car industry. A car needs thousands of times more batteries than a smartphone. Consequently, the global demand for lithium-ion batteries has increased. This demand and advent of different companies besides the investment of some big companies such as Tesla, LG Chem, and Samsung, etc. lead to cost-effective batteries. (LEE, 2020).

There is a necessity for competition and collaboration of big manufacturers to conclude the same result in the marine industry.

3.2.8.3 Government policies

Many governments have supported the electric vehicle market with generous per-car subsidies. Some other countries have required electric utilities to add battery capacity to their grids. Solar panels and windmills have also benefited from subsidies and regulatory mandates. This policy in marine applications also could help to reduce cost and support manufacturers and customers. History has shown that these policies wouldn't be needed forever. Once the battery, solar, and wind industries scaled up, they would become cost-competitive with conventional energy sources even without government subsidies. Based on European Union (2020) research, a considerable number of users of e-ferry have been satisfied because of its quality and being eco-friendly though. Nowadays consumers care about environmental products and it helps consumers welcome these sorts of government policies for e-marine products or services.

An interesting change in USA law demonstrated this consumer behaviour. The federal tax credit for customers who buy Tesla vehicles phased out in 2019, but there's still robust demand for Tesla's vehicles. Nobody pictured this amount of progress in 10 years for electric cars, but it will soon be possible to build an electric vehicle that's directly cost-competitive with internal combustion engine cars with no subsidies at all. And a few years after that, electric cars might be cheaper. That should accelerate the shift toward renewable energy sources even without further government assistance.

The same government strategy is needed for lithium-ion marine application.

In conclusion, these three items which are shown in the following diagram show the most important criteria for battery cost reduction.

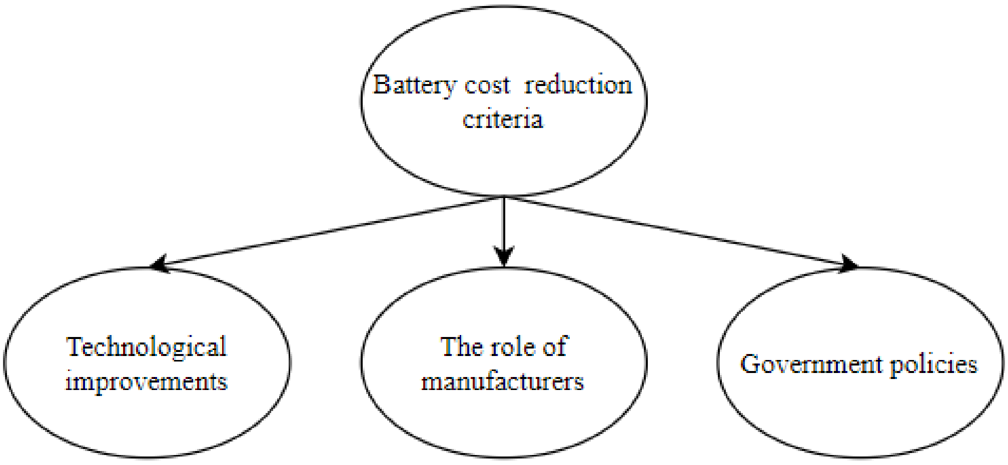


Figure 44 – the macro criteria for the battery cost reduction

3.3 Big players and their role in the future of LIB

Since batteries for vehicles or stationary systems are relied on lithium-ion chemistry, the countries which are rich in lithium deposits, or has invested on this area play a great powerful key role in this wild competitive market at least in short term. Based on the research done by [16], china would be stealing the ball and would overcome the industry until 2025. China would have 80% of raw material, 77% of cell capacity, and has 60% share market of manufacturing. Based on another report [17] more than 70% of lithium-ion factories has been built or under construction are located in China. Over the past decade, huge investments and determining ambitious goals has accelerated the growth of Chinese battery companies and they have changed from nothing to an omnipotent provider of batteries.

Figure 25 shows the mega-factories share in coming years. It illustrates the active mega-factories (red), planned by 2023 (yellow) and planned by 2028 (blue). The highest expansion plans belong to Tesla, LG Chem, CATL, and Wanxiang Group. Afterwards, belong to be BYD Co., Samsung SDI, EVE and JEVE [18].

Figure 26 displays big player in LIB industry based on their production. Based on Palandrani report in **[19], j**ust in a decade mega-factories in the world would have a product combination of 22 Giga factories. Most of the parts are established in china which would have the 57% percent of total.

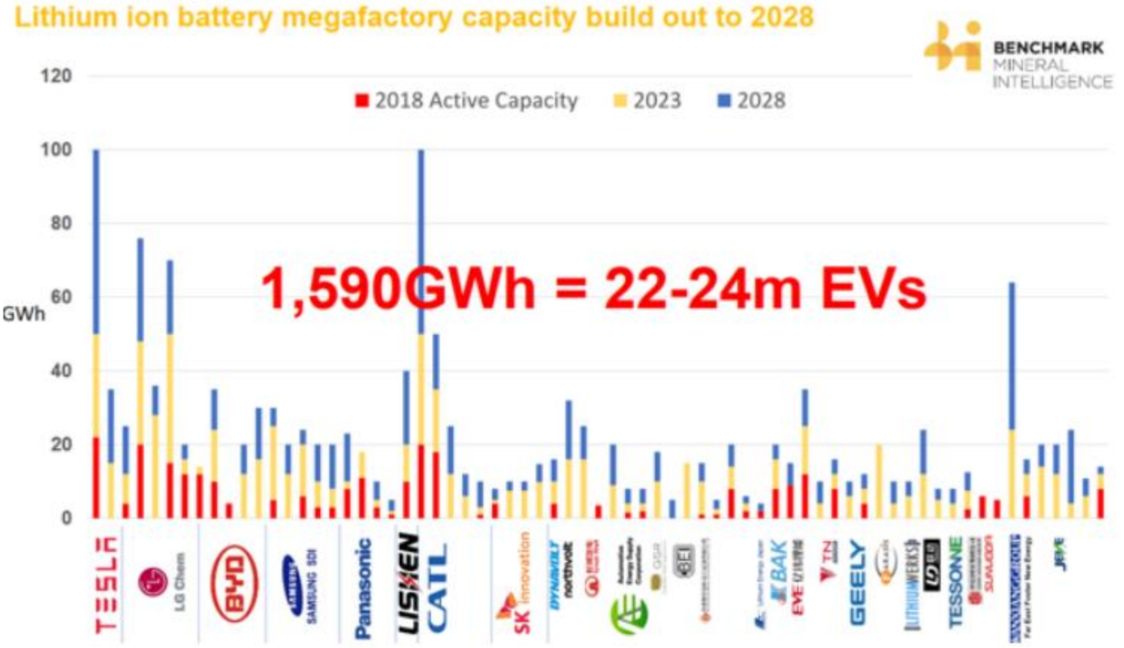


Figure 45 – Mega factory share in coming years [18]

The top ten biggest companies in battery manufacturing in 2020 and 2023 are shown in figure 26 and figure 27 respectively. In 2023 the total production of batteries would be more than 299 GWh and this capacity is half of the global total production.

Figure 46 – Big players in LIB industry [19]

Figure 47 – Biggest Mega-factories by 2023 [20].

The prediction shows 399% increases in demand of lithium-ion battery production capacity for the current decade which would reach to pass 1 TWH milestones. Figure 28 has shaped up the current decade.

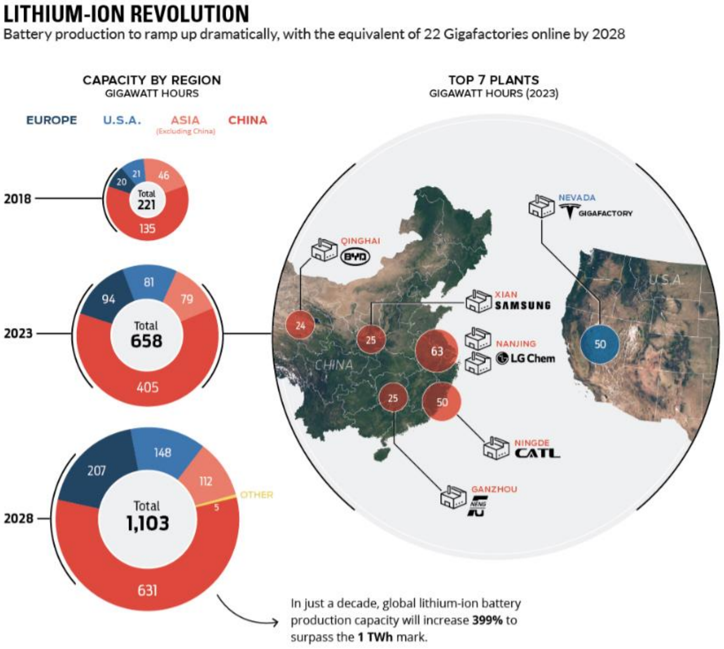


Figure 48 – Capacity production by region. [20]

3.4 Roadmap for battery production and technical characteristics

The market for high-energy-density rechargeable batteries is currently dominated by the Lithium-ion (Li-ion) chemistries, which performs well in most applications. However, current generation Lithium-ion batteries are approaching their performance limits. Without significant breakthroughs, battery performance and production will not keep up with the developments necessary to build a climate-neutral society.

While Lithium-ion batteries will continue to play a significant role in the energy storage landscape, disruptive ideas are required to create the sustainable batteries of the future and lay the foundation for European competitiveness during the transition to a more electricity-based society.

Lead-acid and Lithium-ion batteries dominate the state of the art of today's market for rechargeable batteries, but nickel-cadmium and nickel-metal hydride batteries, as well as some non-rechargeable chemistries, are also produced in Europe. There are also strong efforts to develop vanadium redox flow batteries, mainly for stationary energy storage solutions.

The first commercial Lithium-ion batteries came on the market in the 1990s. Nowadays, the energy density of Lithium-ion batteries has more than doubled while the cost has dropped by a factor of 15. Building on this battery concept, multiple efforts are underway worldwide to further increase battery performance by developing improved storage materials and electrolytes, optimising battery design parameters, and developing more cost-effective and optimised production methods.

The energy performance characteristics for some of the current commercial batteries and possible future chemistries are summarised in Figure 49.

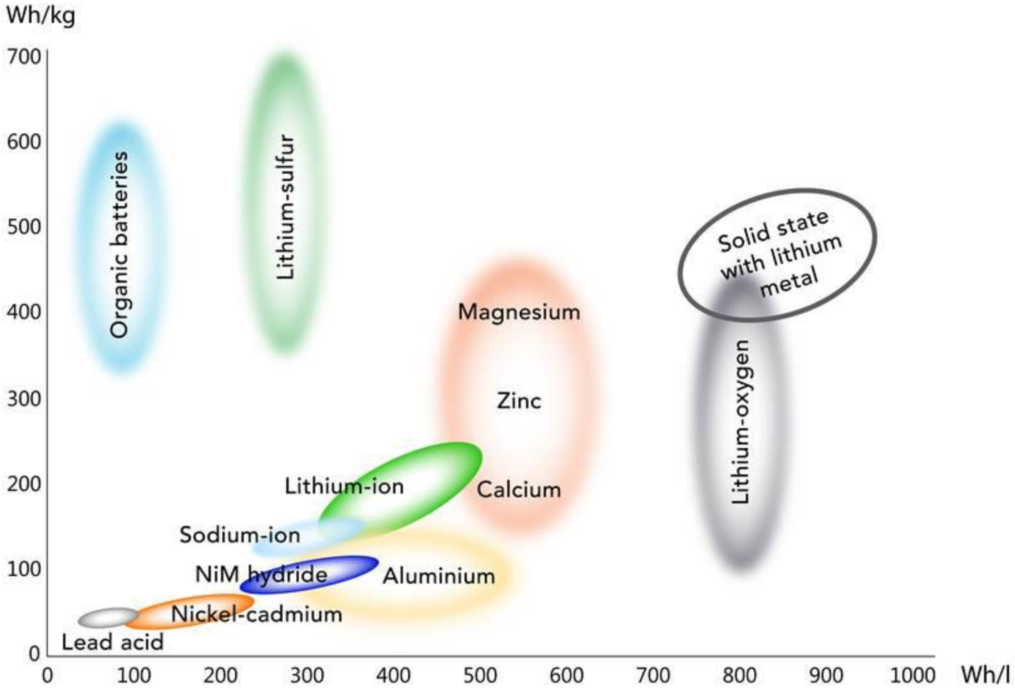


Figure 49 - Energy density vs Specific energy of the most common batteries.

As it can be seen, considerable improvements are expected by innovative lithium-based technologies. Despite the energy characteristics, many other features must be considered for the battery energy storage developments. Indeed, deep investigation on safety, cost, lifetime, and power densities are also required.

In this context, in Europe, safety and hazards involving batteries are regulated by the Battery Directive -Directive (EU) 2006/66/EC, amended in 2018 by Directive (EU) 2018/849 and soon integrated into the upcoming Eco-design Directive for Batteries. Among the others, in these documents, the European Council for Automotive R&D EUCAR set specific safety levels for battery cells and packs to be used as guidelines for judging battery quality [1].

The cost of batteries is, of course, highly relevant. Today’s price for state-of-the-art Lithium-ion batteries packs is roughly € 123–98/kWh. The expected cost will decline to well below € 82/kWh by 2024, a cost level that all future batteries must reach to be competitive [6].

Power is an important parameter. A high-power capability is necessary, for example, to charge a vehicle rapidly. The main limitation is nowadays given by the transport of ions through interfaces within the battery cells. Such a limit is mainly given by the intrinsic characteristics of the materials, which means that new cell designs and materials need to be discovered.

We are now entering a phase in which the increase in energy performances is levelling off for Li-ion batteries, so new solutions and ideas are sorely needed. It will be difficult or even impossible to satisfy future requirements for electrochemical energy storage using solutions based on current technologies.

Special attention is paid to future chemistries important for the transport industry and stationary storage.

An idea of the development of future batteries is given by analysing the roadmaps published by several associations and countries. As an example, Figure 50 shows a comparative assessment of the development timetable up to 2035 published by the European Council (EASE [7], EMIRI [8], EUCAR [1]), China [9], Japan [10], Finland [11], India [12], USA and other associations.

According to the EU's previsions in the SET Plan, the green line represents the different generations of Lithium-ion batteries and when they are expected on the market. The most ambitious target is USA Battery 500, which foresees those solid-state batteries as early as 2022–2023. China and Japan have expectations that are very similar to the European ones. They are almost overlapping the main targets, with the solid-state battery project on the market around 2030.

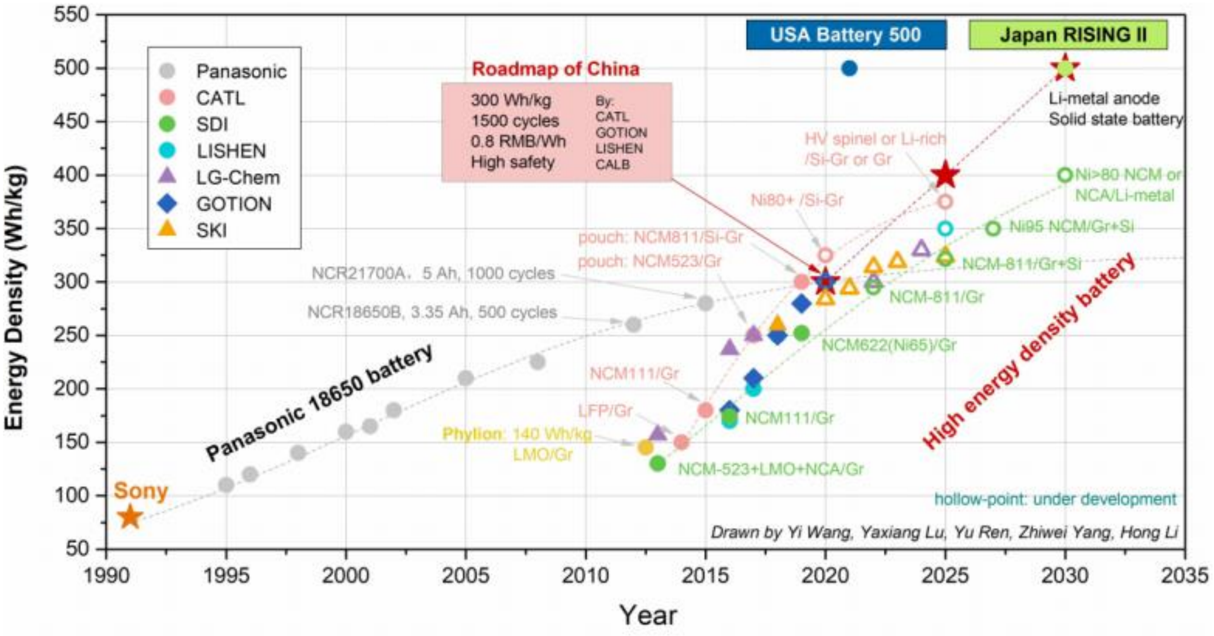


Figure 50 - Comparison of the gravimetric performance of different batteries for automotive applications.

3.4.1 Focus on maritime applications and target at 2030-2035

Considering the marine sector, Figure 51 reports an estimation of the total energy installed onboard worldwide nowadays and its likely future trend. Such evaluation has been already discussed in the previous document of the current project “*Market Evolution and Potential within 5/10/15 years - Total battery capacity installed*”.

The estimation and forecast of the total batteries weight is given by multiplying the point of the green line (European goals) in Figure 50 times the estimated curve of total energy installed, Figure 51. The estimation is presented in Figure 51.

The two tables below (Table 4 and Table 5) illustrate the Key Performance Indicators (KPIs) for Waterborne Transport. In both of them, with reference to “ship lifetime” target, it is to be noted that the average age of a seagoing ship is around 20-25 years, while the average lifetime of inland vessels is even longer (40-60 years). Further, important assumptions for the analysis proposed in these tables are an increase of the market share for marine batteries starting from current 0.2 GWh to 4 GWh and from few kWh to 2.5 GWh in 2035 (as evaluated in Deliverable 1.2 of this project), for energy and power applications, respectively. This increase in the market share would be related with a battery system price drop from the current 600€/kWh to 250-300 €/kWh and from 130 €/kWh to 600 e/kWh in 2035, for energy and power application, respectively.

At the same time, an increase of the cycle life (with reference to 80% of the system state of health) of the battery system is expected in 2035, starting from the current 5000 cycles up to 10000 cycles for energy applications in 2035 and from 25000 to 80000 cycles for power applications.

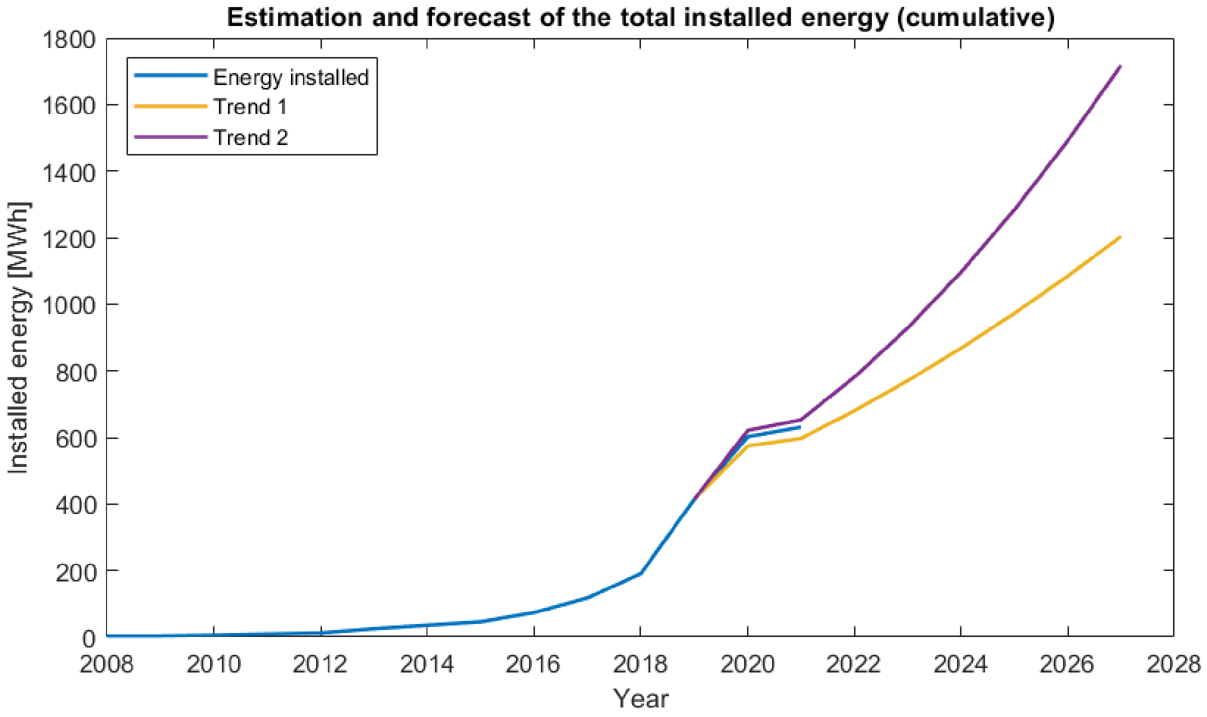


Figure 51 - Estimation and forecast of the total installed energy (cumulative).

Table 4 -- Battery electric or hybrid electric ship with energy battery (cruise ship, ferry, …)

Typical battery size: 500 kWh – several tens of MWh		***ESU: Energy storage unit**	
		Current	**Target 2035**
Typical market size (GWh/year)		~0.2	~4
KPI (ESU* level)	Conditions	State of art	Target 2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	60	70
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	30	60
Operating lifetime expectation	10 years of operation	~50,000-80,000h	(<ship lifetime)
Cost (€/kWh)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	600-700	250-300
KPI (cell level)	Conditions	State of art	Target 2030
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C	~180	350
Volumetric energy density (Wh/L)	1C charge and 3C discharge, 25°C	400-500	800-1,000
Cycle life [80% SOH] (nb of cycles)	70% DOD, 25°C, 1C charge and discharge	5,000-8,000	>10,000
Hazard level	EUCAR cell-level safety performance	<=5	<=2
Cost (€/kWh)		150	75

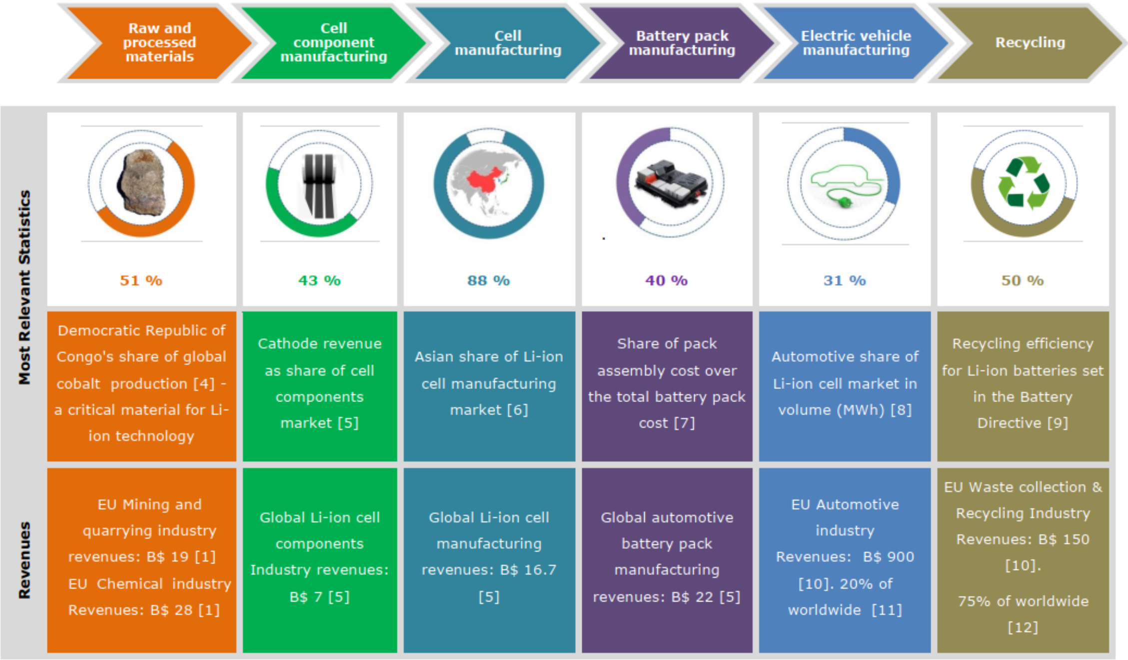
Table 5 -- Battery electric or hybrid electric ship with power battery (offshore vessel, drilling vessel, hybrid fuel cell, ...)

Typical battery size: 100 kWh – several hundreds of kWh		***ESU: Energy storage unit**	
	Source	**Current**	**Target 2035**
Typical market size (GWh/year)		~0	~2,5
KPI (ESU* level)	Conditions	State of art	Target 2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	60	70
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	30	60
Operating lifetime expectation	10 years of operation	~50,000-80,000h	<ship lifetime
Cost (€/kWh)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	1,300	600-700
KPI (cell level)	Conditions	State of art	Target2030
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C	~100	200
Volumetric energy Density (Wh/L)	1C charge and 3C discharge, 25°C	200	400-500
Cycle life [80% SOH] (nb of cycles)	25% DOD, 25°C, 4C charge and discharge	25,000-50,000	>80,000
Hazard level	EUCAR cell-level safety performance	<=5	<=2
Cost (€/kWh)		300	150

3.5 Required skills for battery energy storage systems

LIB is a hot issue in the energy science due to its advantages. LIBs are usable in different industries such as transportation, consumer electronic & devices, and grid energy & industry. This report concentrates on transportation section. There are plenty of vehicle companies that are changing their products from ICE to EV and this shift is concluded from the abundance of LIB components and its green environmental impacts.

In battery production there are different phases which should be considered. The Figure 52 shows the six steps of battery from cradle to grave [2].



	Raw and processed materials	Cell component manufacturing	Cell manufacturing	Battery pack manufacturing	Electric vehicle manufacturing	Recycling
Most Relevant Statistics	51 %	43 %	88 %	40 %	31 %	50 %
	Democratic Republic of Congo's share of global cobalt production [4] - a critical material for Li-ion technology	Cathode revenue as share of cell components market [5]	Asian share of Li-ion cell manufacturing market [6]	Share of pack assembly cost over the total battery pack cost [7]	Automotive share of Li-ion cell market in volume (MWh) [8]	Recycling efficiency for Li-ion batteries set in the Battery Directive [9]
Revenues	EU Mining and quarrying industry revenues: B$ 19 [1] EU Chemical industry Revenues: B$ 28 [1]	Global Li-ion cell components Industry revenues: B$ 7 [5]	Global Li-ion cell manufacturing revenues: B$ 16.7 [5]	Global automotive battery pack manufacturing revenues: B$ 22 [5]	EU Automotive industry Revenues: B$ 900 [10]. 20% of worldwide [11]	EU Waste collection & Recycling Industry Revenues: B$ 150 [10]. 75% of worldwide [12]

Figure 52 – Automotive LIBs value chain [2].

The battery manufacturing part for the desired skills in this report focuses on cell component manufacturing, cell manufacturing and battery pack solutions. These three phases could be done in different companies or all could be operated in one company. In this report we suppose that all the three phases operate in one company.

To define human resource and desired skill requirement for LIB production it would be better to know what components it has and how the process of the production is.

LIB has four main parts consisting of two electrodes, anode, and cathode, immersed in an electrolyte, and separated by a polymer membrane which is shown in Figure 53.

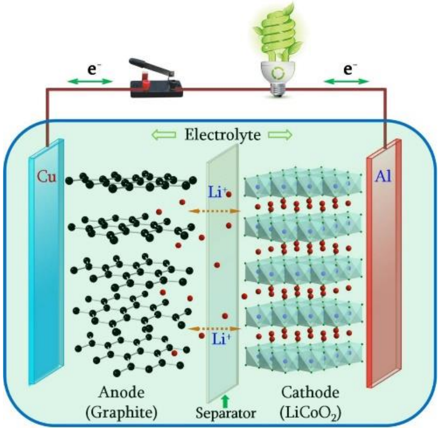


Figure 53 –An illustration of LIB [3].

The cathode, anode, and electrolyte are the most significant materials that identify the performance of LIB. These three materials show which specialties are more desired and in fact they are determinant factors that display the necessity of LIB manufactory from design to production. Especially cathode, anode and electrolyte are the main sub-category of cell component manufacturing. Figure 54 shows a sight of battery company process.

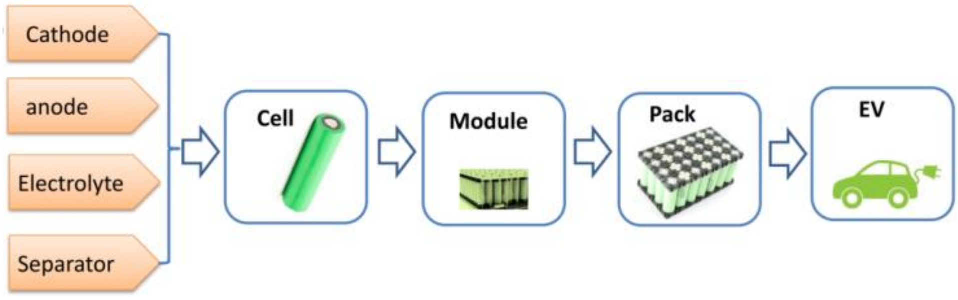


Figure 54 – The schematic diagram of the manufacturing process of battery packs for EVs [1].

As the aim of this report is to address necessary skills for producing of LIB, we propose an organizational chart in which all required specialties and occupations are displayed in Figure 55.

The battery engineering is an interdisciplinary field and most of the concepts are related to different areas. So, the required skill and the related information has been categorized to six areas under supervision of the chef executive officer (CEO).

3.5.1 Administration department

Includes finance, accounting, human resource, marketing, and Information Systems department in which there are different experts. This expertise should be knowledgeable in general computer science skills, communication, and financial analysis. For instance, it is essential to be experienced in database management systems, SQL, and manufacturing software systems. Besides, excellent communication skills including written and verbal negotiation is a necessity. Strong analytical multitasking, and problem solving-skills beside SWOT analysis are key skills for information systems department.

3.5.2 R&D department

R&D department is an influential sector in LIB production considering rapid growth of technology in LIB industry.

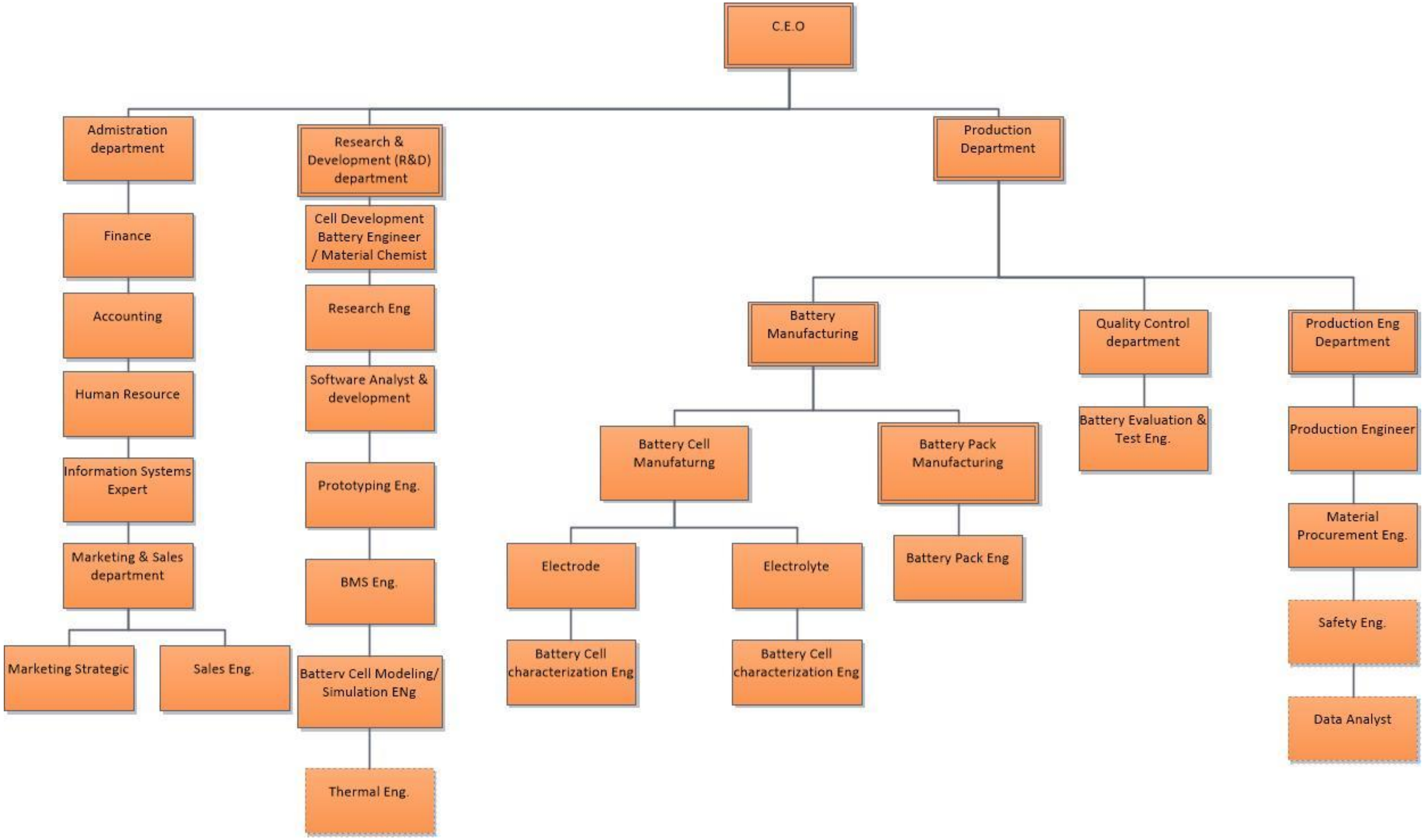


Figure 55 – Organizational chart of LIB production company.

3.5.3 Cell Development Battery Engineer / Material Chemist

The cell development battery engineer develops, produce, and commercialize innovative cell designs based on state-of-the-art commercial and proprietary materials. The responsibilities of this position will cover cell design, development, analysis, and support for product launch. Material chemist utilizes a strong theoretical and working knowledge of cathode, anode, electrolyte, and separator materials, as well as how these components work together to make a successful cell. This engineer needs to meet electrochemical skills experience with analytical chemistry e. g. GC, DSC, experience in electrochemical characterization e. g. cyclic voltammetry, impedance spectroscopy, cycle life testing, and abuse testing. In addition, excellent analytical skills, data analysis and statistical interpretation, familiarity with battery testing standards/protocols, battery cyclers, cell chemistries and formats. More importantly, creating simulation models with predictive capabilities in different software.

3.5.4 Research engineer

The Research Engineer work under R&D group lead with the primary role of synthesizing battery material including doping and coating and testing small electrochemical vehicles to evaluate battery materials. This individual will be required to operate software used to program and run the battery testing instrument, as well as to process and report test data in a standardized format. Experiencing in batteries and electrochemical systems are primary knowledge that a research engineer should have. This engineer needs to meet some electrochemical techniques such as CV, EIS, GITT, and PITT. Furthermore, it is important that the research engineer be familiar with electrochemical cell teardown, failure mode analysis and synthesizing cathode powders with furnaces which needs doping and coating knowledge. In addition, the research engineer should have computer science skills including processing, recording, and tracking test data with different software. Likewise, it is needed to be familiar with statistical process control, and design of experiments in data analysis tools.

3.5.5 Software analyst & development

This engineer should show the capability of working with various cross-functional teams to develop requirements for new battery features, diagnostics, algorithms, etc. Designing, implementing, and testing cutting-edge algorithms for run-time battery logic to derive State-of-Charge, State-of-Health, State-of-Power and State-of-Energy computations are as important responsibilities of this job opportunity. This engineer develops and enhances existing battery models to ensure real vs. simulation accuracy. The software engineer also is responsible for designing rapid test iteration framework for developers to use for quick, at-desk spot checks. Moreover, Expertise should know how to test devices and debugging hardware such as oscilloscope, logic analyzer, and DMM. This engineer should be able to think creatively and produce “outside of the box” solutions. Furthermore, it is important to be experienced in analysis and stimulation of network communication, and schematic design & capture. This engineer needs to meet basic electrical as well.

3.5.6 Prototyping Engineer

Prototyping engineer is responsible for full product design responsibility, from concept through production launch and ramp with different tools which shows how important is that this engineer should be experienced in manufacturing processes such as plastic injection molding, metal stamping, extrusion, welding/brazing, plating, heat treating, and bonding. The engineer is as a part of 3D design team and GD&T drawings of complex parts and assemblies. This individual is needed to be experienced in defining test plans, designing test setups, and analysing data. This engineer should communicate with suppliers for DFM and optimize designs via analytical, numerical, and/or empirical assessments.

Finally, this individual should be capable of evaluate competing design approaches using any one of the various development tools (DFMEA, fault tree, decision matrices, etc.).

3.5.7 BMS Engineer

The BMS Engineer is responsible for the design, development, and execution of Battery Management System (BMS) cell components and controls applications in LIBs. The BMS engineer is responsible for specifying, implementing, and validating control algorithms related to LIB systems. This engineer needs to be well versed in software and controls development, battery algorithms, functional safety, and CAN communications as well as typical development tools. This engineer needs to be experienced with modelling of LIB cells, specifying or executing tests on cells, and diagnostic techniques for cells components. Moreover, this individual needs to simulate dynamic models of electrical systems and be able to analyse algorithm performance in distinct software. The BMS engineer should be knowledgeable in linear systems analysis and estimation algorithms design. Finally, this engineer should have strong communication and preference for working in teams.

3.5.8 Battery Modelling/Simulation Engineer

This engineer develops and maintains advanced mathematical models to predict lithium-ion cell performance and aging characteristics. The engineer also is expected to propose and develop test methods to validate physical models. This engineer needs to meet electrochemical & computer science skills. For instance, this individual should be experienced with system CAE tools, and lab-scale battery cell fabrication and electrochemical characterization methods. The battery modelling engineer needs to be fluent in computational tools and software languages. An excellent teamwork and communication skills is highly needed for this job.

3.5.9 Thermal Engineer

The engineer is responsible for conducting LIB system level thermal analysis, and battery module/pack level power performance simulations. This engineer needs to meet mechanical skills for instance, be experienced with PPAP process. This engineer should be familiar with FEA, CAE, and CFD, and thermal analytical tools and thermal management system simulation. Moreover, it is essential to know PFMEA, DFMEA, and DVP&R. Likewise, this individual should have excellent quality, manufacturing, and product assurance planning skills and be able to resolve conflicting requirements across multiple organizations. Finally, the thermal engineer should possess excellent leadership and interpersonal skills.

3.5.10 Production department

Production department includes three principal departments: battery cell manufacturing, battery pack manufacturing, production engineering department.

3.5.10.1 Battery Manufacturing

There are two distinct departments in battery cell manufacturing as follow.

3.5.10.2 Batter Cell manufacturing

In this department battery cell characterization engineer is plays a key role in two sub-categories of battery cell manufacturing: electrode, and electrolyte.

3.5.10.2.1 Battery Cell Characterization Engineer

The battery cell characterization engineer should evaluate and select cathode, anode, and electrolyte materials that meets requirements. Also, it is necessary to develop materials for different applications. Working with cross functional teams internally and externally is the responsibility if battery engineer to bring new cathode, anode, and electrolyte technology to cell production. This engineer should define cathode, anode, and electrolyte development roadmap for cell technology and be an expert leader in the technical discussion and lead the collaboration with external research laboratory. This engineer needs to meet computer science and electrochemical skills such as EIS, GITT, CV, PITT techniques. This engineer also needs to be experienced with material characterization such as SEM, XRD, and DSC. This individual is necessary to have knowledge in material synthesis and doping and surface modification. Having specialty in electrode processing including making slurry, coating, calendaring, and drying is essential. Battery cell characterization engineer should have strong knowledge about development process to improve cathode, anode, and electrolyte performance and cycle/calendar life and be experienced in building coin cells and assembly cylindrical cell. This engineer should work with glovebox and dry-room, handling air-sensitive materials.

3.5.10.3 Battery pack Manufacturing

In this department battery pack engineer plays a key role.

3.5.10.3.1 Battery Pack Engineer

The battery pack engineering team works on multifaceted structural, electrical, and thermal problems. This individual helps to test and drive the safety design of highly integrated batteries and have a major influence on product direction. This engineer should be experienced in structural, electrical, thermal, and mechanical systems and has strong analytical/problem solving skills and general mechanical engineering analysis. Also, it is expected that the battery pack engineer be experienced in in test fixture design and fabrication; 3-D CAD and be able to analyse and manage test data from large data sets. This engineer needs to meet mechanical skills such as PPAP process, manufacturing, and product assurance planning skills. Moreover, this engineer should possess excellent leadership and interpersonal skills beside good communication, problem solving, computer and presentation skills. The Battery pack engineer is supposed to understand PFMEA, DFMEA, and DVP&R and be familiar with FEA, CAE, and CFD, and thermal analytical tools

3.5.11 Quality Control Department

This department is responsible for checking the manufactured products and communicate with R&D, production line, and even cell design for making improvements through organization. Battery evaluation and test engineer plays this key role and is described as follow.

3.5.11.1 Battery Evaluation and Test Engineer

This position is in the Battery Testing Team and be responsible for electrical testing, mechanical testing, and electro-chemical characterization of LIB within the Enervate test labs. This engineer needs to meet mechanical and electrical skills, for instance this engineer should be able to operate and troubleshoot all testing equipment and electronic inspection tools e.g. meters, scopes, Arbin, Maccor. Moreover, the engineer is supposed to be familiar with computer based statistical analysis software, database experience including SQL, designing software, and data acquisition and analysis software. The battery evaluation and test engineer must have Basic working understanding of Statics, Thermodynamics, Heat

Transfer, Fluid Mechanics, Solid Mechanics, Dynamics and Vibration, Electricity and Magnetism, CAE, Measurement and Instrumentation, and Linear Circuits.

Furthermore, this individual should be experienced with hand tools, power tools, and machine shop safety and be able to design of test setups for mechanical and thermal performance testing, such as fixtures for shock and vibe testing. His main responsibility is creating and executing design validation plans and test methods to validate performance requirements which needs strong working experience with hydraulic/electric/pneumatic actuators or other actuation systems. Strong working understanding of Analog Electrical Design, and a basic working understanding of Active Circuit Design, Energy Conversion, Power Electronics, Digital Circuits, and Motor Drives is necessary for this job. As this job is critical it needs extra skills in terms of understanding of Kinematics, Solid Mechanics, and FEA, and a basic working understanding of Mechanical Behaviour of Materials, Fatigue and Failure Analysis.

3.5.12 Production Engineering department

It consists of several engineers including production engineer, Material Procurement engineer, Safety Engineer, and data Analyst.

3.5.12.1.1 Production Engineer

The production Engineer works in a cross-functional environment to ensure production operates in the most efficient way possible. This engineer optimizes output while reducing non-value-added wastes. This engineer needs to meet production & manufacturing skills including excellent knowledge of production planning and quality control principles and enough experience in MRP II (Manufacturing resource planning). Strong organizational, problem-solving, and communication skills are necessary because of a wide variety communication of this job. This engineer should have PFMEA, and Lean manufacturing implementation skills and six sigma knowledge is highly preferred.

3.5.12.1.2 Material Procurement engineer

This Engineer oversees the purchasing of technical goods and services for the production operation. Material procurement Engineer has very detailed knowledge of the equipment, materials and supplies used in LIB industry, and are able to identify companies that sell them. The engineer could evaluate suppliers and negotiate purchase agreements with them, as well as maintain the inventory of supplies. This engineer needs to meet production & manufacturing skills consisting of MRP II (Manufacturing resource planning) experience, excellent communication abilities, and quality control skills.

3.5.12.1.3 Battery Safety Engineer

The Safety engineer is responsible for supporting safety and reliability across product through the delivery of reliability test development and execution, timely failure analysis, and driving strategic initiatives. This engineer needs to meet electrical and mechanical skills including rechargeable lithium-ion battery chemistries and technologies. This engineer should have excellent analytical and problem-solving skills beside evaluating and selecting forms of empirical analysis, modelling, and testing methodologies to validate product designs and specifications. Likewise, this engineer is supposed to be experienced in driving conclusions through analytical techniques including CT X-ray, SEM, FTIR, and optical microscopy.

3.5.12.1.4 Data Analyst

This expertise is responsible for developing tools to analyse batteries delivered to customers as well as manufacturer production and R&D data. The expertise performs research to support design and development of battery systems, cells, and other sub-components. This engineer needs to meet electrical and computer science skills including experience with mathematical modelling of physical systems, experience in data evaluation and statistical methods in technical / electrical environment, and experience in evaluation complex data sets. Data analyst is supposed to be knowledgeable in working with analytical software.

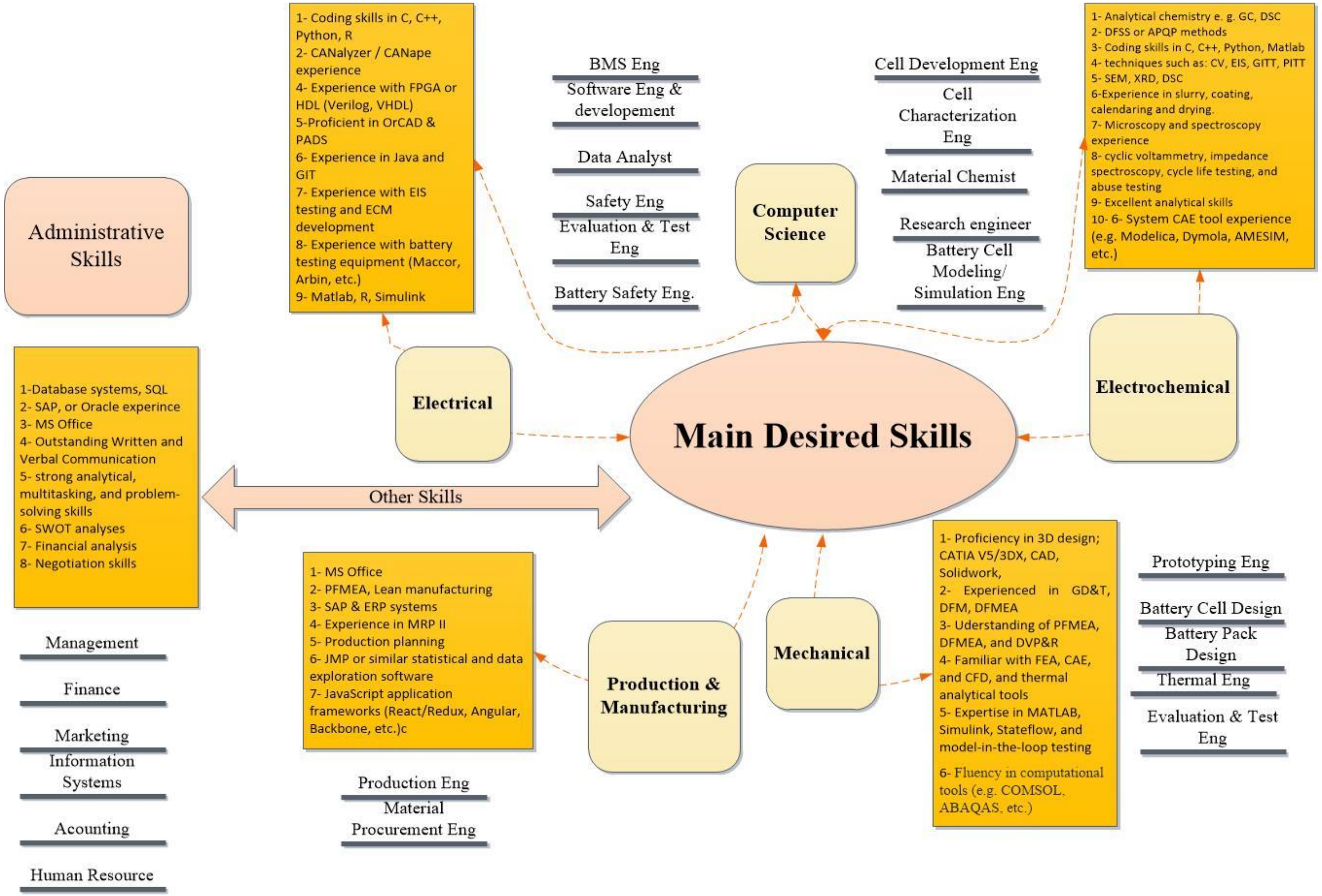


Figure 56 – A brief schematic of desired skills

3.6 Technological challenges and bottlenecks for the battery on-board integration

In this section are presented the technological challenges and bottlenecks for the battery installation on-board.

3.6.1 Cost of onshore electric energy

The cost of onshore electricity is a challenge for battery evolution, especially in the perspective of charging full electric ships by onshore connection. A high cost of electric energy could stop or delay the increase in the use of batteries on board ship, which is expected for the next 15 years.

3.6.2 Current cost of batteries

Similarly, a constant (or worse an increase) cost of batteries could lead to a delay in the integration of large batteries on board ship. However, this is seen as a challenge rather than as a bottleneck, due to the future battery cost forecasting (presented in the present document).

3.6.3 Patents and certification for personnel

Special licenses and certifications may be required in the future for on-board personnel who manage batteries, very similar to the certifications and licenses required today for on-board personnel who must work with medium voltage systems.

3.6.4 Specific energy

The battery specific energy improvement is one of the main challenges for the near future and, for some applications, also a bottleneck for the decarbonisation. Current specific energy of lithium ion batterie is equal to 180 Wh/kg for energy battery applications. A reasonable target for 2030 is to double this, achieving the 350 Wh/kg in order to enabling the use of batteries for the decarbonisation of the short/medium range vessels.

3.6.5 Charging

During a voyage, typically, a ship consumes electrical energy for propulsion and the hotel loads' supply. The magnitude of the energy demand is about hundreds of kWh and can vary upon weather conditions such as wind and marine currents.

While at berth, a ship requires to recharge its Energy Storage Systems (ESSs) with demand typically about a few MWh. Thus, to minimize the recharge period at berth, the coastline electric grids should manage high powers. Such networks are typically unable to manage these peaks of powers. Therefore, grid reinforcements and the setting up of a new grid station can be required.

Moreover, it must be noticed that the ship's energy demand during the hotelling period is not limited to only battery charging but also includes the energy required to supply the ship's systems, cargo handling mechanisms, etc. Thus, the total power demand could also be higher.

To provide such a power typically, medium voltage (MV) range are required. Typical values are 6,6 kV and 11 kV.

The cost of the whole infrastructure, which may arise to millions of dollars, can be estimated after a thorough study based on several factors to cater for the power requirements.

The utilization of the resources mainly influences the investment payback period.

In the case of low traffic, the grid station might be underutilized to obtain financial benefits from capital spending [17].

3.6.6 Temperature

A Li-ion cell needs to operate within specific voltage and temperature levels to ensure safe operation. This is achieved through a Battery Management System (BMS), which performs control, monitoring, and protective functions for the battery system. If the batteries operate outside the safety limits, the BMS will activate an electrical disconnection of the battery system. The DNV GL class rules require that a battery system have an integrated BMS, without which the system cannot be certified.

The operating temperature of the battery cell must be kept in a specific range. When the temperature is too high, the electrolyte will start to vaporize into flammable gases, and, if heated further, the battery cell can initiate a thermal runaway (exothermic reaction) that might lead to self-ignition of the flammable gases.

If the battery cell is charged at too low a temperature, Li plating can occur. This will shorten the battery life and increase the probability of an internal short in the cell. The safe temperature range depends on the type of Li-battery chemistry and is typically between 0 °C and 60 °C. Additionally, the life span of the battery cell depends heavily on the cell temperature during charging and discharging. The optimal operating temperature usually is around 20–25 °C.

3.6.7 Cycling and ageing

All batteries gradually lose their capacity to store energy. This is caused by cycling the battery or just by storing the battery without using it.

Cycling a battery is the process of charging and discharging it. A discharge, followed by a charge, is known as a cycle.

The process of losing energy storing capacity because of performed cycles is called cycle ageing. The process of losing capacity while being in storage is called calendar ageing.

Much research has been done on the ageing of batteries when performing static cycles. Static cycles are cycles at, for instance, a constant temperature or charge rate. However, not much is yet known about the effects of a dynamic operational profile of a ship on the ageing process of batteries and how to take them into account in the design phase of a fully battery-powered ship. Ships are usually designed to last for about 30 years. With batteries, this is very hard to achieve. Therefore, when designing a battery-powered ship, the aim is generally at an expected battery life of 10 years.

All batteries suffer from ageing, but every type of battery age differently. The manufacturer can give information on the ageing of a specific battery, but the information is usually biased and incomplete.

Ageing can be divided into two different groups based on their consequences, capacity loss and power loss.

There are three leading causes for capacity loss and two main causes for power loss. The main causes for capacity loss are electrode disintegration, material deterioration and loss of free lithium.

The main causes of power loss are surface layer formation and contact deterioration.

The temperature, state of charge, depth of discharge and C-rates are the most investigated causes for battery ageing. They are also assumed to be the leading causes. From a shipbuilding perspective, there might also be other operational conditions influencing the ageing of the batteries [18].

3.6.8 Humidity and pressure

The humidity and pressure in the battery space influence battery ageing. High humidity increases the self-discharge rate of the battery. Low humidity levels can cause the battery to dry out. The pressure always affects chemical reactions, and therefore it is assumed that it also plays a role in ageing.

3.6.9 Thermal runaway & propagation

Thermal runaway is the exothermic reaction that occurs when a lithium-ion battery starts to burn. The thermal event often starts from an abuse mechanism that causes sufficient internal temperature rise to ignite the electrolyte within a given cell. This fire then poses a significant risk of igniting the metallic electrodes contained within the battery cell, thus producing a high-temperature metal (Class D) fire. Additionally, these metals may contain oxygen, which is thus released as it burns. Not all lithium-ion batteries contain oxygen within the electrodes, but all lithium-ion batteries on the market today contain electrolyte that can ignite and cause this thermal runaway scenario.

A maritime battery system is typically made up of thousands of cells. Thus, a single cell's failure and total heat release is a relatively minor threat. The more significant threat comes from that thermal event producing sufficient heat that it propagates to other cells, causing them to go into thermal runaway. As this cascade through the battery, the heat produced increases exponentially, and the risk is developed of a fire in which the entire battery is involved. Thus, battery modules and systems must be engineered to protect against propagation based on the cell used, and these cascading protections are the critical feature of system design for safety [14].

3.6.10 Electrolyte off-gas

The electrolyte contained within a given cell consists of an organic solvent, typically variants of diethyl carbonates. This means that they are flammable, and additionally, this means the gasses that are produced during a failure scenario are also flammable and can present an explosion risk. These gasses also typically contain other species which are toxic – such as hydrochloric acid and hydrofluoric acid. Thus, these aspects of battery off-gas require consideration about ignition sources and ventilation within both the battery module and battery room [14].

3.6.11 Battery Management System - BMS

The battery is only as strong as its weakest link (cell). All batteries within the system will degrade at slightly different rates. A quality BMS system will be best able to minimize those variations as it keeps batteries in balance. In addition, the BMS is responsible for calculating current limits, SOC, and State of Health (SOH). These are all complex functions that require years of experience and in-depth knowledge of the specific battery system. A high-quality BMS system is a critical component of a safe and fully effective battery system.

The BMS is also vital in preventing the converter from overcharging the battery system. Such failures may cause more than one cell or module to fail simultaneously. Note that the most probable scenario for such failures is that any fire or off-gassing will start at the weakest cell or module before spreading to the rest of the system [14].

The BMS are custom made for a pack and are challenging to find. This led to a problem in the replacement after a failure.

3.6.12 Battery cell and chemistry consideration

As stated previously, any lithium-ion battery will burn as it is an energy source. A battery system is built up of tens of thousands of cells. Thus, some of the critical factors regarding safety are ensuring that one battery fails in some sort of thermal event that others around it do not do the same.

A key aspect of this analysis is how much heat is produced by the cell. A larger cell will contain a more significant amount of energy and produce more heat when it burns. Larger cells produce advantages about energy content and density of a system, but system design must be sure to consider this larger size.

Chemistry is also a factor. Most lithium-ion batteries in use are of a Lithium Cobalt Oxide (LCO), Nickel Cobalt Manganese (NCM) or Lithium Manganese Oxide (LMO) type. These chemistries present similarities in having layered metal oxides and producing oxygen during thermal runaway events. Thus, these chemistries will burn more violently and with a more significant amount of heat released. Iron Phosphate (LFP) batteries, on the other hand, do not contain oxygen in the internal metal structures and thus do not produce as much heat in the case of a thermal failure. Additionally, Lithium Titanate Oxide (LTO) batteries will produce less heat during a thermal failure scenario.

3.6.13 Operational safety risks of lithium-ion batteries

In the following, a summary of the primary ways in which a lithium-ion battery can be misused or abused (in such a way that it is at high risk of producing a safety event) is provided. Many of these risks come from an undesired electrical operation, and thus the control system – Battery Management System, BMS – plays a key role in safety, as well as electrical architecture and electrical system protection. These factors are described as they pertain to a cell, but if electrical protections are insufficient, the risk posed by these abuse mechanisms increases exponentially when applied to an entire module or, even worse, a full rack.

3.6.14 Overcharge

Overcharging a Lithium-ion battery represents one of the highest likelihoods and highest consequence scenarios that can occur. Overcharging a battery means charging it to a point where its voltage exceeds its maximum limit. When a battery is overcharged, internal temperature rises, and the electrolyte is at significant risk of breaking down into gaseous constituents.

Both lead to a risk of igniting the electrolyte in liquid or gaseous form. Incorrect communication of SOC from the BMS to the converter or the Power Management System, the imbalance between cells, or even a short circuit producing an excessive charge current are all scenarios that may pose a risk of overcharge. Voltage limits will vary at the cell level depending on battery chemistry [14].

3.6.15 Over discharge

Over discharge represents a scenario where the battery voltage has dropped below manufacturer recommended limits. This can lead to the decomposition of the electrodes within the battery, posing a risk of short-circuiting and heating electrolyte and causing a fire. Also similar to overcharge, the BMS has a prime role in protecting against over discharge. Voltage limits will vary at the cell level depending on battery chemistry [14].

3.6.16 Overcurrent

Overcurrent comes from charging or discharging the battery at a power level that is too high. This can cause excessive temperature generation, thus leading to electrolyte ignition. In addition, this can lead to incorrect voltage management and thus accidental overcharging or over discharging. The converter connected to the battery should be equipped with overcurrent protection, where the BMS sets the limits. In severe cases, the excessive current may be of a fault or short circuit type and thus out of control; thus, passive electrical protections such as fuses, and breakers are the key to prevent this failure [14].

3.6.17 Overheating

Thermal management of a battery system is the key. Excessive temperatures will drive degradation and can also lead to a safety event. If the ambient temperature is too high, then the battery may operate in a way that further increases its internal temperature beyond acceptable limits. Acceptable upper-temperature limits are often near 45°C [14].

3.6.18 Excessive cold

Operating a battery in temperatures below its rated range will increase internal resistance, decrease efficiency, and lead to a safety event through lithium plating on the anode or formation of dendrites, resulting in an internal short circuit and rapid heating of the electrolyte. Lower temperature thresholds range widely between different cell chemistries, and manufacturer recommendations should be followed closely, but it can generally be considered inadvisable to operate below 10°C [14].

3.6.19 External short circuit

An external short circuit is likely a familiar concept and poses the same risk as many other failure modes described in this section. If the battery is rapidly charged or discharged, the electrolyte in a cell may heat to the point of ignition and pose a threat of thermal runaway and/or flammable or toxic off-gas release [14].

3.6.20 Mechanical damage

Mechanical damage may result from external protrusion into the battery room under collision, errant crane operation, or perhaps in the case of explosion or other mistakes. If a cell is mechanically damaged, a risk is posed of the electrodes coming into contact and short-circuiting and many other electrical components. This short-circuiting thus produces the same failure mode of heating the electrolyte to the point of ignition [14].

3.6.21 External fire

An external fire poses the threat of involving the battery system and thus directly overheating and combusting all battery materials. An external fire might also heat the battery space such that the ambient temperature exceeds the acceptable limit of safe battery operation. Proper fire segregation of the battery room and a fire extinguishing system that removes the heat from the battery space is then important [14].

3.6.22 Internal defect

An internal defect represents perhaps the largest threat to a lithium-ion battery system because it cannot be detected by the battery BMS. Most of all, other failures will result in indications from voltage or temperature sensors that will be detected and accounted for by the BMS. An internal defect may produce an internal short with little to no warning. This is the result of issues or quality control from manufacturing. Although many cell producers maintain a high degree of quality control, the large number of cells required for an installation and the inability to detect make an internal defect a significant risk and the main reason that off-gas and thermal runaway must be considered and protected against in even the most highly controlled and monitored systems [14].

3.6.23 Summary of challenges and bottlenecks

The above technological problem can be classified into challenges and bottlenecks (see Table 6).

- Bottlenecks are related to technological limits and must be assessed in the design.
- Challenges are related to the intrinsic characteristics of each technology which may create hazards. They must be considered and properly managed by the designer.

Table 6 - Challenges vs Bottlenecks.

NAME	CHALLENGES/BOTTLENECKS
Cost of onshore electric energy	Challenge
Cost of batteries	Challenge
Patents and certification for personel	Challenge/Bottleneck
Specific energy	Bottleneck
Charging	Bottleneck
Temperature	Challenge/Bottleneck
Ageing	Bottleneck
Humidity	Challenge/Bottleneck
Thermal runaway & propagation	Challenge
Electrolyte off-gas	Challenge
Battery Management System (failure)	Challenge
Battery cell and chemistry	Bottleneck
Overcharge	Challenge
Overdischarge	Challenge

Overcurrent	Challenge
Excessive cold	Challenge/Bottleneck
External short circuit	Challenge
Mechanical damage	Challenge
External fire	Challenge/Bottleneck
Internal defect	Bottlenecks

4 Discussion, Conclusions and Recommendations

4.1 Conclusions

As the research has explained because of the higher specific energy, power and the great performance of Li-ion batteries, they have penetrated into all levels of industry. In addition, it is projected that the battery cost would reduce more and more in the coming years because of increasing in demand for EV industry and consumer electronics market. Furthermore, it is expected that the price of battery reduces further for coming years, due to the increasing demand from the electric automobile industry and the consumer electronics market. The primary components of a Li-ion battery include modules composed of an assembly of cells, which comprise electrodes, electrolyte, and separators. Battery prices decreased by more than 80 percent, from €1043/kWh to €180kWh from 2010 to 2017, and it is predicted the price will reach approximately €75kWh within the next 8 years. The role of oil will have been changed by 2035 and batteries determine the power of each section in the economy. In term of design, LFP and NMC become the most powerful game changers. As all model shows the cost reduction is not a linear model and it decreases exponentially. Therefore, the battery cost might decrease even with a much sharper slope.

However, in such a context, it is also to be highlighted that maritime battery systems are more expensive than land-based systems, due to their necessary "marinization" (e.g. the modification of the battery system in order to be able to safely operate in the marine environment). In fact, not being developed specifically for the maritime industry already at the cell and then at the system level, it is necessary to adapt these systems to be able to install them on board in an efficient and, above all, safe way for the ship and people.

As illustrated in Figure 43, these estimates in fact align quite well with the overall development in maritime battery systems from suppliers, as well as with the exponential decrease in cost that applies to other packs of lithium-ion batteries, e.g. for electric cars, although EV battery packs are typically only one-third the price of maritime packs, as the latter are produced to higher standards for class approval and safety.

Thus, the expected cost-cutting effect for battery systems will also affect marine applications, although costs will remain higher than those presented for land-based applications. In this sense, the development of modules and systems already designed for installation on board ship (as in the scope of this project) could significantly help to reduce these associated costs.

The results of the research analysis and this document, relating to the future cost of battery production volumes for marine applications, have highlighted a future cost target of the battery system for marine use of approximately 250-300 € / kWh (complete system) with production volumes that should settle between 3 and 4 GWh of installations, as summarized in Table 4 and Table 5 for energy and power applications, respectively.

Furthermore, in this report, the human resource of a company for designing and producing lithium-ion battery was studied. The first question that should be answered is: what kind of departments are necessary for this sort of business. After wide research on fortune companies in this field such as Tesla, Panasonic, CATL, etc. the report has divided the human resource to three categories. Figure 56 demonstrates a brief graph of desired special skills for producing LIBs.

Finally, this paper has proposed an analysis of the main bottlenecks and challenges that need to be addressed in the future for the integration of battery systems on board ships. As summarized in Table

7 below, the main bottlenecks concern: patents and certification for personnel, temperatures and humidity (especially in some regions with extreme weather conditions) and external fire.

Moreover, there are several challenges that should be faced, event with a different grade of difficulty.

Main challenges, especially for the full decarbonisation, are: the cost of onshore energy (with the need to get tax-free rates to be competitive with traditional fuels), battery cost, specific energy and ageing, which have a direct impact on the possible integration on board of large volumes of batteries and on their expected lifespan, and related replacement costs.

Table 7 - Challenges vs Bottlenecks.

NAME	CHALLENGES/BOTTLENECKS
Cost of onshore electric energy	Challenge
Cost of batteries	Challenge
Patents and certification for personel	Challenge/Bottleneck
Specific energy	Bottleneck
Charging	Bottleneck
Temperature	Challenge/Bottleneck
Ageing	Bottleneck
Humidity	Challenge/Bottleneck
Thermal runaway & propagation	Challenge
Electrolyte off-gas	Challenge
Battery Management System (failure)	Challenge
Battery cell and chemistry	Bottleneck
Overcharge	Challenge
Overdischarge	Challenge
Overcurrent	Challenge
Excessive cold	Challenge/Bottleneck
External short circuit	Challenge
Mechanical damage	Challenge
External fire	Challenge/Bottleneck
Internal defect	Bottlenecks

4.2 Recommendations

One of the main topics that can be addressed in the future of this project and, more generally, in the future of battery systems for marine applications, is the theme of the optimal choice of cell chemistry and their possible combination (i.e. hybrid battery storage systems) to increase the performance of the overall system (costs, dimensions, energy and power). In fact, some manufacturers have already begun to bring systems of this type to the market. However, the further challenge is to find the optimal mix for different maritime applications, at least waiting for the next technological developments and "winners take all" solutions that can revolutionize the market and the application of battery systems on board the ship.

Another important aspect to take into account is the life span of the batteries. this, in fact, has a direct impact on both the sizing of the system and the cost. At present, in fact, the common goal is to guarantee a battery life of at least 10 years. As shown in Figure 57, it is possible to increase the lifespan of batteries by limiting their DOD. To limit the DOD for the same energy use of the battery system, it is necessary to oversize the system itself, with evident effects on both the overall dimensions and the costs of the system. In this context, tools for selecting the most appropriate technology would be useful (as evident in Figure 57, the choice of different technologies directly impacts on the number of guaranteed life cycles) and optimal sizing of battery systems to minimize costs and dimensions and guarantee the required lifespan, also taking into account the costs of replacing the system with respect to ship life.

Often, the most commonly used chemicals (NMC and LFP) involve an important oversizing of the system (between 30 and 40%) to guarantee an adequate number of life cycles. The choice of technologies such as LTOs, although more expensive from a CAPEX point of view, could lead to lower costs in relation to the entire life of the ship.

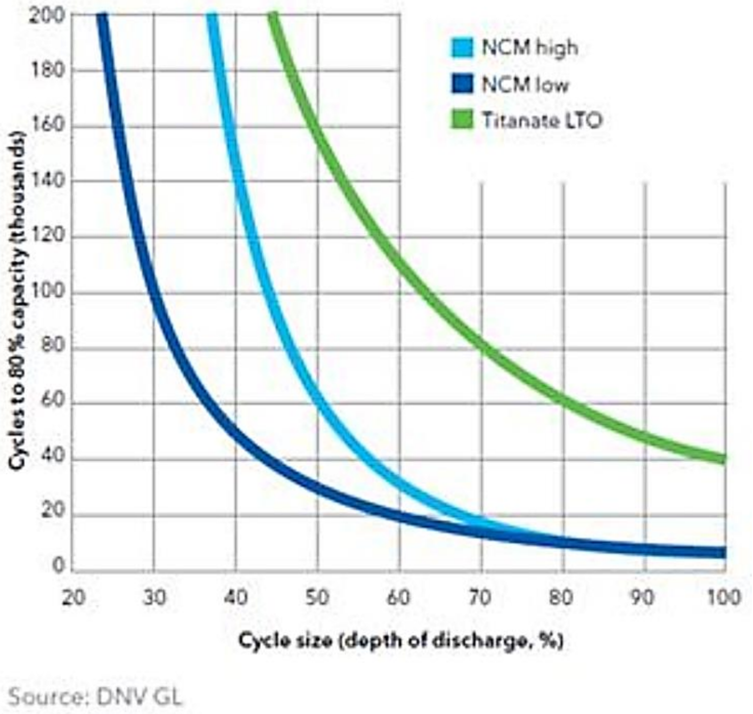


Figure 57 – Number of life-cycle of different batteries depending on their Depth of discharge (DOD)

Finally, both the BMS of the battery systems and the EMS on board ship, should be developed to maximize the life span of the battery system, especially for those applications where the batteries perform a support function for the power generation system. In the case of full electric ships that work by operating only on battery systems, load management techniques would be required that allow greater flexibility in power management, in order to extend the useful life of the batteries and thus reduce the related costs.

5 Deviations from Grant Agreement Annex 1

There are no deviations with respect to Annex 1.

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Project partners:

#	Partner	Partner Full Name
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4	RINA	RINA SERVICES SPA
5	SOERMAR	FUNDACION CENTRO TECNOLOGICO SOERMAR
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12	IKERLAN	IKERLAN S. COOP
13	MGEP	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP
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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