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Mathematical framework for total cost of ownership analysis of marine electrical energy storage inspired by circular economy

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HIGHLIGHTS

• LIB industry volumes are skyrocketing, thus efficient material circulation is essential.
• LIB material circulation enables significant new revenue streams and opportunities.
• For marine application owners retired LIB residual value can decrease retrofit cost.
• Life cycle cost of marine batteries may decrease ca. 20% of second life reuse.

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ABSTRACT

The strongly growing uptake of lithium-ion batteries (LIBs) in transportation requires environmentally sustainable ways to treat spent batteries. Novel material circulation processes establish material flows which create significant business opportunities and new jobs and welfare. This paper develops a mathematical model for considering the circular economy in the life cycle costs in the maritime sector. Current articles and models do not quantify economic gains from the LIB circular economy, especially in the marine sector. An additional challenge is that the typical planned lifetime is 30 years which means that the battery energy storage of a ship needs to be retrofitted 1–3 times over the ship’s lifetime. The analysis herein considers the cost evolution of ESS during the coming decades to estimate retrofit battery costs and re-use economics. The main finding of the study is that battery material circulation can be conducted in all phases over the lifetime of the marine application and clear revenue streams are identified. These are not only decepting the costs for battery investment, but are also able to bring revenues, leading to commercially viable reuse of batteries. However, it is also concluded that material circulation requires more technological, procedural, and industrial innovations during the coming years.

1. Introduction

Total global energy consumption has increased by more than 62% between 1990 and 2018 (International Energy Agency (IEA) [1]) and more than 80% of this increase was covered by fossil resources. Growing population, especially in developing countries, is coupled with growing consumption for products and services which in turn fuels the upward trend in global energy consumption. This constant increase, however, has adverse effects on our living environment via global warming. Climate change due to greenhouse gas (GHG) emissions and its mitigation have been on the agenda of world leaders since the Kyoto Protocol (adopted in 1997), covering 192 countries. The European Union aims to reduce its GHG emissions by more than 80% below their 1990 level by 2050 [2]. In addition, the EU has set an objective (June 2021, European Climate Law) to reach net zero greenhouse gas emissions in EU by 2050 [42]. This climate package also includes the FuelEU Maritime Initiative, impacting ships and ports. Some of the most important methods to achieve these targets are increasing the share of renewables in the energy sector, electrification of applications, hydrogen and e-fuels, end-user energy efficiency and transitioning to a circular economy. The increasing electrification of end-user sectors and industries has created a need for high-level deployment of energy storage, including the storage of electrical energy and hydrogen.

In the past decade, the electrification of transportation has seen a considerable expansion and this trend is expected to continue for the foreseeable future. The manufacturing capacity of LIBs for mobility and stationary energy storage applications is ca. 150 GWh, and global annual
The battery demand is predicted to reach about 1000 GWh by 2030. By 2040, according to projections, global annual sales of LIBs may increase up to 4 TWh [3]. The expectation is that economies of scale through mass manufacturing can halve the cost of LIBs between 2018 and 2030 and an additional reduction of 50% may be achieved by 2040. As mass production enables more affordable energy storage for the transport sector, the electrification of maritime transport will also take off. As of 2018, the maritime industry (total shipping) emits 1015 million tonnes of CO₂ per year which is ca. 3.1% [4] of global CO₂ emissions and, as of 2015, maritime transport accounts for 13% of transport related greenhouse gas emissions in the EU [5]. In April 2018, the International Maritime Organization (IMO) has agreed to reduce total annual GHG emissions from shipping by at least 50% until 2050 compared to 2008 levels [5]. Large scale LIB storage systems are becoming a very important enabler of reduced greenhouse gas emissions and ecologically sustainable marine transport. For example, zero emission coastal and inland ferries, supplied with clean renewable energy sources, can eliminate 100% of the GHG emissions on the routes where they are applicable [6].

State of the art battery systems for fully electric propulsion, along with peak shaving, spinning reserve and dynamic range extension can be used to achieve the targeted annual reduction of GHG emissions in the marine sector, when combined with clean energy sources. In addition to operational GHG emission reductions, emission reductions from manufacturing through cleaner processes must be promoted. Finally, the implementation of circular economy principles can achieve a clean-up of the whole value chain, including raw material extraction [7,8], battery product design, manufacturing, operation, and disposal. As a part of the circular economy concept, the second-life use of battery modules and packs also introduces important means to reduce overall GHG emissions and ownership costs [9]. Thus, the implementation of circular economy principles to the electrification of maritime transport could result in significant cost savings for owners, manufacturers, and society.

Previous studies have examined the circular economy and waste management for LIBs in electric vehicles (EVs) (Richa et al. [9]; Pagliaro et al. [10]) along with the related theoretical material flows, including reuse recycling, energy recovery and landfill. Cumulative energy demand, metal input and economic benefit have been estimated to be positive for reuse and recycling compared to alternatives. Harper et al. [11] highlights the need for more efficient processes to improve the environmental and economic viability of recycling and points out that a range of non-technical factors such as collection, transportation, storage, and logistics have an impact on recycling performance. Transportation aspects were also examined by Slattery et al. [12]. Other researchers have been evaluating the technical feasibility [7] and process capabilities for recycling [13], as well as recycling GHG emissions and costs [14]. Recovery efficiency in studied commercial processes for Li from LIBs was reported to be 76–95% with up to 99% purity levels [7].

Second-life use of LIBs is another important material circulation path where the residual value of the battery can be utilized [15]. For the second-life repurposing cost estimation National Renewable Energy Laboratory NREL has provided a calculator together with the U.S. Department of Energy DOE [16,17]. The study of second life EV battery usage for peak shaving in a stationary distribution network during high power demand shows significant environmental benefits compared to other peak handing technologies, but revenue opportunities remain un-quantified [18]. Steward et al. [19] have evaluated the economics of recycling from the battery material viewpoint and concluded that up to 43% cathode cost saving could be achieved via recycling compared to usage of virgin raw materials. Analysis by Cicconi et al. [20] shows that the second life usage of batteries with LiFePO4 cell chemistry allows an additional 1000–1300 cycles after end-of-life (EOL) that can be utilized in smart grid storage. This study demonstrated the technical and environmental feasibility of using second life batteries, but the authors recommend the undertaking of deep economic assessment.

A lot of human and financial capital today is invested in the research and development of battery chemistry, with the aim of increasing energy density, power density, lowering prices, extending life and improving safety. Research focuses on new cathode [39], anode [40] and electrolyte [41] technologies, structures and materials. Technological changes affect material recycling processes, necessitating changes therein. In addition, the use of less critical and cheaper materials can reduce the profitability of recycling. However, we will not yet discuss the circular economy of future battery chemistry in this article.

A life-cycle cost model is essential when the project must minimize the cost of ownership throughout the whole lifecycle, not only acquisition cost, as described by Ellis [21]. Life cycle cost (LCC) takes into consideration all costs arising from acquisition, management, operation and disposal of the asset. Lee [22] introduced an approximation model for investment residual value based on remaining service life (RSL), but in case of battery products, the residual value is also impacted by the market price of new batteries at the moment of the retrofit. Schmidt et al. [23] have used levelized cost of storage (LCOS) based mathematical modelling for 9 electrical energy storage technologies to evaluate their lifetime cost of storing energy. With LCOS comparison they concluded that LIBs are likely to become the most cost efficient option for nearly all stationary applications from 2030.

Nevertheless, in the studied literature there is no concrete quantification of the impact of circular economy on the life cycle cost of LIBs. Hence, more evaluation is needed to clarify how much CE can improve economics for vehicle owners, ship owners or battery manufacturers in the coming decades.

This article will discuss the economic modelling of electrified transportation, including circular economy opportunities in maritime industry. We aim to quantify the available economical gains for total cost of ownership from the ship owners’ and manufacturers’ perspective. The economical evaluation must gather all the key cost elements related to construction, operation, and disposal of batteries during their lifetime, compare them with conventional vessel technologies. Total cost of ownership covers initial capital expenditure, operational costs - such as energy, maintenance and crew costs - as well as disposal costs, including related material streams.

In this work, the goal is to analyse the lifecycle cost of marine electric energy storage systems (ESS) and find out the potential economic gains achievable by circular economy from the vessel owner’s perspective. In addition, environmental benefit potential is discussed. The EU Waste Framework Directive 2008/98/EC [24] advocates this circular thinking
with the waste management hierarchy of prevention, reuse, recycling, recovery and disposal. The focus of this study is on the ‘reuse’, ‘repair’ and ‘recycle’ stages. Fig. 1 depicts the waste management hierarchy and shows circular economy strategies for the marine LIB energy storage products.

Considering the projected scale of LIB deployment, whereby global annual sales in 2040 reach 0.6 TWh – 4 TWh [3], efficient EOL waste management processes for batteries are required. In addition to the re-use, recycle and recovery processes, it is important to reduce the amount of waste via careful design for end-of-life processing and for a long product life span [25]. The design of products that fit to circular economy means optimizing the product lifespan from the sustainability perspective, without compromising the economic viability of the product. Circular or closed-loop economy aims to reduce waste by cycling the products and materials to reach high resource efficiency and high energy efficiency as well as improved profitability [9].

While a CE type of efficient waste management strategy is an essential requirement to avoid pollution and save scarce metals, the efficiency and economical side of the processes require a lot of attention and efforts to be profitable. Forecasts indicate a significant decrease of LIB prices [3], up to 50% each decade. On the other hand, during the last 5 years we can see a significant increase in the price of raw materials, specifically for Cu and Ni and fluctuations in the price of Co, Li and Mn. World market metal prices have a direct impact on the profitability of recycling.

The strong growth of LIB usage in EVs will transform the LIB industry and reuse/recycling industries to extremely high-volume businesses. This will lead to optimized processes with lower cost per ton or kWh. In the research literature the overall economic gains of circular economy for vessel lifetime cost have not yet been thoroughly evaluated, and the novelty of this research is to bring concrete insight into this from a technical and economic perspective.

2. Battery circular economy model in marine industry

A circular economy process for transport applications aims to delay or avoid disposal flows and utilizes the European Union Waste Framework Directive (Directive 75/442/EEC of 15 July 1975) waste management hierarchy of prevention, reuse, recycling, recovery and disposal [24].

Circular waste management includes multiple routes for circulation [9]. Fig. 2 depicts the LIB material flows from the marine application perspective, where typically several batteries are required during the lifetime of vessel. In normal application usage, maintenance enables direct re-use of the energy storage systems (ESS) within the same application. Re-use of the ESS’s parts in less demanding applications either within marine systems or in stationary systems, such as on-shore charging stations constitutes a second-life application of the battery. Recycling of battery materials is the next pathway for both batteries after second-life and materials not passing quality control. Energy can be recovered and the remaining portion goes to landfill.

Direct re-use of the ESS within the same application or second-life re-use in stationary energy storage normally requires some adaptation and qualification testing work and possibly the replacement or refurbishment of some materials, such as cells/modules with inadequate performance. Recycling and recovery of materials typically require several mechanical process steps such as dismantling, sorting, crushing, separation and pyrometallurgical and hydrometallurgical processing. Encouraging research results for recycling suggest that purities up to 99% and recovery levels of 89%–99% for LIB electrode materials (Co, Cu, Li, Mn, Ni) can be reached [7,13]. Material which cannot be recycled economically, such as plastics, can be combusted to recover energy [9]. Finally, nonrecoverable material from recycling operations will be sent to landfill.

In this article, we analyse a fully electric large marine application. It is assumed that the LIB must be changed twice during the lifetime of a vessel. For all used LIBs we can analyse all relevant circular material paths and the environmental and economic metrics could be evaluated. Economic metrics shall include life-cycle cost with and without a circular economy approach.

2.1. Direct reuse in electric transport application

Direct reuse of the LIB means using the battery in the same application from which it was obtained. In large marine applications we can assume that the energy storage consists of tens of parallel battery banks. In the vessel there are many different energy needs, such as propulsion, hotel load, peak shaving, emergency energy reserve, strategic loading, and spinning reserve. Using flexible drive train architectures and power control algorithms, it is possible to consider and define different use and load profiles for batteries of different age groups and performance capabilities. This enables the direct reuse of some end-of-life batteries in the same vessel for less applications with a demanding usage profile. For example, the maximum allowed power load can be reduced and the frequency of usage can be reduced or re-scoped.

To achieve this, the battery bank requires testing and

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**Fig. 1.** High level model of circular economy, mapped to the maritime industry.
characterization before re-use to be able to dimension the rest of the lifetime with renewed usage parameters. Product direct re-use is also enhanced by advanced diagnostics functions and by designing simple repair processes [25]. To improve validation, entire service-lifelong collection of battery degradation data is under discussion and research [26].

This reuse model can save owners costs since part of the battery banks do not need to be replaced. New generation batteries typically require less floor space, so the vessel’s original battery compartments can house the same amount of energy even when some batteries have reduced capacities. There is also potential to decrease the investment and assembly costs of second and third LIB bank retrofits. In addition, disposal and related transport costs will be lower.

2.2. Re-purposed battery reuse

Re-use of EOL LIB in stationary systems, such as in onshore marine containers or stationary grid connected energy storages with lower performance requirements, is a valuable opportunity to save both in terms of cost and usage of scarce raw materials. Traditionally, traction batteries are dimensioned to be used until capacity or peak power has degraded to 80% level [14,15]. Research studies suggest that second-life use can extend the cycle life by 50%–65% [15,26]. For example, batteries with LiFePO₄ cells could continue working for another 2000 cycles until their capacity reduces to 60% [20].

A stationary battery with a less demanding duty cycle could mean for example a use case where battery undergoes less than one cycle per day, or where the cycle depth of discharge (DoD) is low and the required power levels for charging and discharging are lower for new batteries. Battery could be used as PV solar energy storage where the battery is charged with a low current (low C-rate) during the day and used with low current during the night, i.e. for balancing the peak usage of grid energy. Also, re-use of the second-life batteries as backup energy sources for telecom, energy storages for events or accessory services, and grid balancing for frequency control services demonstrate that there are many less demanding use cases which create viable opportunities for a second-life battery [26,27]. Ultimately this also means the possibility to procure clearly more economical battery, since the second life battery prices are estimated to be close to 50% of the price of new batteries [3]. In addition, the price of new EV battery packs are expected to decrease to 100 €/kWh level by 2030 compared to 200 €/kWh in 2019 [3]. McKinsey [27] estimates second-life batteries to have 30–70% cost advantage. Conversely, Martinez-Laserna et al. [15] estimate second-life LIB prices to range from 44 to 180 $/kWh, which would position them as affordable alternatives of new LIBs. In this article, the refurbishment costs range from 25 to 49 $/kWh. An important cost item, which should not be neglected, is the cost of transportation of retired batteries. Slattery et al. [12] summarize transportation cost from different sources and
sets the range between 0.24 and 5.51 $/kg, with the average accounting for 41% of the total recycling cost. Due to the low raw material extraction cost of end-of-life batteries compared to recycling, re-used batteries are estimated to be 5 times cheaper. This will be a strong driver of the second-life battery market with a compounded annual growth rate (CAGR) of 23.1% during 2020–2030, according to Bloomberg [28].

Similarly, we can consider reusing an EOL propulsion battery which has reached 90%–80% of its original capacity for second-life usage within a vessel. When there is need to do an energy storage retrofit for a vessel, the renewed configuration can be a combination of the latest ESS technology and reused battery banks. Obviously new and re-used battery banks must be managed separately from the power management and electrical architecture perspective, so that the technical limitations and roles are under control. Typically, new ESS technology enables a significantly higher energy capacity for the same footprint and weight compared to older generation models. Thus, when using combination of old and new technology, the total capacity can be kept the same or even increased in the same footprint. Possible secondary use cases for reused batteries could be in the emergency energy reserve, peak shaving usage, hotel load usage or blackout-prevention, where duty cycles are run rather rarely and where the required current levels are relatively low.

Second-life re-use also gives the owner an opportunity to consider the potential revenue via selling used batteries for onshore stationary purpose and receive some payback via reuse instead of paying disposal costs. Moreover, onshore stationary second-life batteries can be used for cost savings via storing renewable energy during cheaper tariff times, e.g. during the night. Energy can then be used for example for electric ferry traffic during the day, when electricity is more expensive. If part of the used battery banks is allocated to a new purpose in a vessel as described above, there are potential cost savings through the opportunity to dimension a smaller new battery and also obtain savings in assembly costs. In the second life battery business economical model we can identify components’ “second life selling price”, “re-purposing costs” and “residual value” of the LIB. Residual value and re-purposing costs together build up the second life selling price. Re-purposing costs include testing, refurbishing, transportation, facility capex and other costs.

In addition, second-life re-use of LIB can also create significant environmental benefits. Ahmadi [18] has estimated that the CO2 emissions over the lifetime of 18 years via second life stationary re-use of (PHEV/WIND) batteries amount to 56% compared to the combination of single life LIB and natural gas usage (PHEV/NG). The CO2 emissions associated with LIB re-purposing have been estimated to be low (5.9%) compared to life cycle CO2 emissions of PHEV.

### 2.3. Battery material recycling

Current LIBs generally use a graphite anode and a cathode made of lithium metal oxides. Typical cathode chemistries in transport are lithium-nickel manganese cobalt (NMC), lithium-iron-phosphate (LFP), lithium titanate (LTO), lithium-cobalt oxide (LCO) and nickel-lithium cobalt aluminium oxide (NCA) [14,18,29]. Battery systems are generally composed of mechanical racks or enclosures containing battery modules, which aim to create strong environmental protection for a number of LIB cells. Typical battery storage voltages in transport applications range from 300 Vdc to 1100 Vdc.

In addition to active materials, the recycled battery includes Al and Cu in foils to support the active materials, as well as in cables and electrical parts and Fe, Al and plastics in enclosures and modules. A recycled battery cell contains as an average composition ca. 51% cathode materials, 31% anode materials, 7% plastic waste, 7% metal waste, 2% binder and 1% electrolyte [30]. The average composition of cathode materials is: lithium 6.1%, cobalt 56.1%, nickel 0.8%, manganese 0.7%, oxygen 36.1% and others 0.1%. Table 1 introduces battery storage materials of a complete marine battery system including battery modules, battery management, cooling systems, cabling and rack mechanics, based on an example electric ferry battery configuration [6].

| Material | % of weight | kg |
|----------|-------------|----|
| Steel    | 21.2%       | 12018 |
| Stainless steel | 4.1% | 2310 |
| Aluminum | 18.8%       | 10691 |
| Copper   | 11.7%       | 6639 |
| Brass    | 0.2%        | 139  |
| Plastics | 12.7%       | 7216 |
| Lithium  | 0.6%        | 363  |
| Cobalt   | 2.7%        | 1559 |
| Nickel   | 3.2%        | 1793 |
| Manganese| 2.5%        | 1403 |
| Graphite | 8.0%        | 4570 |
| Electrolyte | 6.8%    | 3844 |
| Aluminum oxide | 3.5% | 2016 |
| Miscellaneous | 4.0%    | 2259 |
| Total    | 100%        | 56,820 |

At present there are several different recycling processes to re-introduce valuable LIB compounds or elements back into use, which are thoroughly reviewed elsewhere [7,31]. Fig. 3 illustrates the general model of the processes used for recycling and the recoverable materials. Typically, the recycling process includes mechanical phases in the order of disassembly, dismantling, sorting, shredding, milling, gridding and again sorting of materials, aiming to concentrate the valuable elements. In the next phase, electrode materials are treated with various combinations of hydrometallurgical and pyrometallurgical processes to recover cathode and anode precursor materials or metallic elements.

The economic value of a raw material varies significantly over time. From trading market price statistics, we can note the following changes between the start of years 2019 and 2021: Cu +36%, Ni +46%, Co 0% and lithium carbonate −27% [32]. Hence, industrial scale recycling process profitability is significantly impacted by the variation in prices, especially cathode material prices – particularly that of Co, as seen from the weight percentages in Table 1. It is also worth noting that battery industry is looking for chemistries with a lower proportion of Co which can have a significant impact on recycling economics. The economic question is: will recycling of cathode material influence the world market price? This is hard to answer since the battery production volumes and recycling volumes are growing in parallel. In this analysis, it is assumed that material recycling is taken into account in the world market pricing of EV energy storages [3].

Existing literature about recycling indicates a strong potential for LIB recycling both in terms of economic and environmental impact, especially when higher volumes are reached [19]. Recycling also reduces the environmental impact compared to the mining of virgin materials, but recycling to the elemental level still requires a lot of energy and therefore higher levels of circular economy should be aimed for. Overall, recycling can lead to a significant reduction of environmental impacts associated with the production of LIB cells and, hence, it is crucial for the future LIB industry. However, benefits also depend strongly on the chemistry of the processed cell [33]. The recycling industry must also consider the future changes in material composition, so that process adaptability to future changes could be an advantage [34].

### 2.4. Energy recovery

It is not commercially or technically feasible to recycle all parts in LIBs. For example, plastic materials cannot be easily re-used as such due to changed form factors and new plastic part designs of new LIB generations, as new generations often target to denser layout, better manufacturability or other gains requiring mechanical improvements. Some cell related plastic parts wear out in use and can also be contaminated, so they are not reusable, even if they could be dismantled intact. The non-recoverable material amount on a marine vessel equipped with 4.3 MWh
of LIB capacity could be estimated to be ca. 7216 kg [6]. Table 1 depicts the main material categories and volumes. The key assumption here is that the plastic materials are not commercially feasible to recycle, so plastics, as solid waste (SW), could be directed to a waste-to-energy (WtE) process through incineration [35] or gasification [36] to recover the energy. Residues of the incineration process are typically landfilled as the final disposal method. Incineration also significantly reduces the waste disposal need, resulting in lower disposal costs. Utilizing combustion energy output estimates for plastic solid waste [35] we can calculate the potential energy recovery for the large marine battery introduced in Table 1. This plastic waste incinerated will produce ca. 204746 MJ/57 MWh of energy [35].

In addition to the recovered energy, incineration plants produce ca. 5–5.5% [22] of ash and other landfill material compared to the original weight of waste material feed. Ash may be used for several purposes including landfill, road construction, road stabilization and forest fertilization, but the quality of ash, especially considering the possible heavy metal contamination, may result in some limitations to its usability.

The landfill also incurs a cost component. The current cost of ash landfill in Finland/Kymenlaakson Jäte is 140 €/Tn [37]. Higher costs can also be found in the literature, such as US$ 1.170/Tn for LIB landfill including collection cost [9]. Most likely regulation and landfill costs will drive towards the minimization of landfill from batteries.

3. Methods

In this chapter we introduce a mathematical model to estimate the LCC of the LIB and the electric ship. A significant part of our analysis is the economic calculation on the storage side, but also the impact on the complete marine application cost level has been analysed. The models to capture the economic impact of circular economy (CE) on the overall life cycle cost (LCC) are described in less detail. In the following chapter, LCC models are developed further to cover CE in a more comprehensive way.

3.1. Life-cycle cost model

Life-cycle cost (LCC) is a technique to evaluate the total cost of ownership over the life of an asset and draw comparisons between mutually exclusive alternatives. It is also referred to as “cradle to grave” cost. Direct cost categories are acquisition costs, usage costs, maintenance costs and end-of-life costs. The overall cost may be compensated by the residual value. The typical LCC model with cost components and present value (PV) calculations are described e.g. by Ellis [21] and Lee [21]. Typical LCC models include three main components: the capital expenditure of acquisition, yearly recurring costs and, finally, the EOL disposal cost or the residual value. If there is remaining value, the last cost component can be negative, i.e. it reduces the LCC. In LCC models the cost is calculated for the entire lifetime and discounted to the present value by using the capital discount rate (r) and time (t). Next, we will elaborate equations to analyse the impact of circular economy of energy storage on the life cycle cost of a marine application. In this analysis we must consider that the ESS must be replaced several times during the life of the application. On a higher level, we can describe LCC as

\[
LCC = C_{\text{Cap}} + PV_{\text{Recurring cost}} - PV_{\text{Residual value}}
\]

where \(C_{\text{Cap}}\) is capital expenditure, \(PV_{\text{Recurring cost}}\) is the present value of annual costs and \(PV_{\text{Residual value}}\) is the present value of the remaining value of the LIB. During the life cycle of the vessel, the investment in energy storage (LIB) can be described as:

\[
C_{\text{Cap}} = \sum_{n=0}^{T} \frac{C_{\text{Cap},n} T_n}{(1+r)^n}
\]

where \(T\) describes how many times the LIB is renewed during the vessel’s lifetime, \(T_n\) is LIB lifetime in years and \(r\) is the discount rate [%].

Operational cost PV includes yearly operation and maintenance cost and
charging cost as present value:

$$PV_{\text{Recurring}} = \sum_{t=1}^{T} \frac{C_{\text{OMM}} + C_{\text{CH}}}{(1 + r)^t}$$

(3)

where $C_{\text{OMM}}$ represents operation and maintenance costs during the year $t$, $C_{\text{CH}}$ is charging costs over the year $t$, and $(T+1)^{r}T_{r}$ is the application lifetime in years.

During the lifecycle of the vessel, the disposal cost and the residual value shall be considered $T+1$ times. $PV_{\text{NV}}$ (4) is the residual net value for the owner.

$$PV_{\text{Residual Value}} = \sum_{t=1}^{T} \left( \frac{V_{\text{ref}}}{(1 + r)^t} \right) - \frac{C_{\text{de}}}{(1 + r)^t}$$

(4)

where $C_{\text{de}}$ is the LIB removal and disposing cost and $V_{\text{ct}}$ is the LIB re-sale value for second life repurposing.

For second life use, the LIB incurs costs for disassembly work, transportation, assembly, and validation testing. The complete expression for the life cycle cost of the energy storage subsystem of the ship takes the form

$$\text{LCC} = C_{\text{Cap, ship}} + PV_{\text{Recurring}} - PV_{\text{NV}}$$

(5)

$$= \sum_{t=1}^{T} \left( C_{\text{Cap, ship}} + \frac{V_{\text{ref}}}{(1 + r)^t} - \frac{C_{\text{de}}}{(1 + r)^t} \right)$$

(6)

and the application level (ship) life-cycle cost will take form of

$$\text{LCC}_{\text{ship}} = C_{\text{Cap, ship}} + PV_{\text{Recurring}} - PV_{\text{NV}}$$

(7)

where $C_{\text{Cap, ship}}$ is ship investment excluding LIBs, $PV_{\text{Recurring}}$ is operational costs including crew, energy, maintenance, service, insurances and other yearly costs.

3.2. Recycling economics

At the end of life of a battery, the recycling phase recovers raw materials from the battery which have been in primary use in propulsion and reused in a stationary second life application.

Current literature contains a broad range of estimates for the cost of disposal. However, this study uses real-world commercial quotes for the sake of accuracy. Disposal cost examples:

- NMC 1k€/ton - 2.5 k€/ton
- LTO 3.5k€/ton - 4.0 k€/ton

The important question is whether this material could have value for the EOL ESS owner, rather than cost only. On the other hand, if the end user can return the batteries to the manufacturer free of charge (FOC), how much economic benefit can the manufacturer get from recycling. In the following analysis, we assume that the revenue $R$ for the recycling facility would be:

$$R = P \cdot N + \sum P_{i} N_{i} - C_{P} + N - C_{f}$$

(8)

where $P$ is the disposal fee per ton, $N$ is the disposed material in tons, $C_{P}$ is the recycling process cost per ton, $P_{i}$ is the market price for extracted raw material i per ton, $N_{i}$ is the amount of recovered material i in tons and $C_{f}$ is the fixed cost of the facility normalized to $N$.

The material that can be recovered may depend on the process type and the battery chemistries, but the main elements recovered with the current processes are Fe, Cu, Al, Co, Li, Ni, and Mn. The profitability is heavily dependent on world market prices of raw materials and on the density of each material in the disposed and processed batteries. Recycling process economics is therefore a broad subject and requires further studies to achieve a full understanding.

4. Results

This analysis focuses on the economic impact of LIB re-use throughout the application’s lifetime, observed both in the LIB and ship level LCCs. Since the lifetime of a ship can be over 30 years, the LIB shall be changed several times and hence in this analysis we need to forecast the evolution of LIB investment cost, second-life price, and disposal cost for 2-3 decades. During that time, the battery chemistries, the battery manufacturing processes, and the recycling and re-use processes will also evolve significantly. This has a significant impact on the process efficiency and economy. This part of the analysis obviously has a lot of unknown factors from the forecasting perspective. Also, mineral prices will fluctuate over the years and for example Co and Ni prices will impact both the profitability of the recycling process and the pricing of the new batteries.

4.1. Life cycle cost analysis

In this study, we have selected a fully electric ferry as a case study. Life cycle cost of this vessel is calculated for 36 years, using a discount rate of 3%, an initial capital investment of 16.750 M€ and yearly operating expenses of 1.700 M€. Investment includes costs for design, the hull, outfitting, propulsion, electrical systems, automation, battery systems, the onshore charging station, approvals, a one-time 10 kV connection fee and 2 automooring-systems (= automatic docking) and VAT [6]. Operating expenses include crew costs, energy costs, maintenance costs, insurances, and other costs. Other costs include the maintenance of onshore installations, ticketing equipment, taxes, and fees.

We selected a 4.3 MWh battery on NMC111 cell chemistry for this case. The weight of the LIB, divided into forward (FWD) and rear (AFT) battery compartments, is 57 tons. The LIB configuration includes 840 battery modules located in 80 energy racks and 20 control racks, in addition to related control and power cabling, liquid cooling, and ventilation.

The LIB retrofit price is forecasted for years +12 and +24 was taken to be (2032) 323 €/kWh and (2044) 213 €/kWh, whereas during the initial investment year 2020 the cost was 490 €/kWh. The future pricing of second-life batteries is challenging to forecast, but there are some attempts nonetheless: McKinsey predict second-life batteries to be 30 – 70% less expensive compared to new ones in 2025 [27], whereas Tsipoulos et al. assume that batteries can be re-sold to manufacturers at 50% of the cost [3] – this assumption is somewhat optimistic. The US Department of Energy together with National Renewable Energy Laboratory have created a LIB repurposing cost modelling tool [16], which also helps with analysing the cost breakdown related to re-purposing. In this study, we are assuming that the sales price of second-life LIBs could reach 50% of new LIBs’ market price, which is the midpoint of McKinsey’s estimate. This suggests that the prices users could get from selling old LIBs to re-purposing companies is even lower, as there are certain re-purposing and business costs to be covered that have to be covered by the re-selling price. Repurposing processes incur costs related to preparing the second-life battery, which includes testing, assembly, transportation, facility capital and variable costs and other costs. After the first lifetime of the battery, the LIB in the vessel is retrofitted, providing the owner with an opportunity to recuperate the residual value of a LIB which can be expressed as the second life LIB re-selling price discounted with the repurposing costs. The residual value of an old LIB can be significant for the ship owner at the time of investing into a new LIB for retrofitting. Here, it is assumed that all 3 LIBs are of the same nameplate capacity of 4.3 MWh.
4.1.1. Retrofit LIB cashflow impact

This analysis suggests that the economic gain from selling LIBs for second life use can create revenue of over 30% compared to the price of a new replacement LIB. In addition, at the end of the life of the third battery (+36 years) there is a sizable residual value for the ship owner at the EOL of the ship. Fig. 4 depicts the potential residual value of each retired battery compared to the new battery investment during the particular year.

Fig. 4 shows that during each retrofit year, the residual value of retired battery is relatively large compared to the investment cost for the new LIB, ca. 34–35%. In addition, at EOL of the ship 175,000 € of residual value is available for the ship owner. Net re-purposing process costs and testing in this estimate are assumed to be 14% of the value of the new LIB, NREL [16]. Additionally, disassembly and packing costs (3.1 €/kWh) for the retired battery are taken into account. As a conclusion, the indicated cost savings are significant for the owner and, at the same time, the second-life usage of LIB helps reduce GHG emissions.

4.1.2. LIB life cycle cost capex impact

Here, the analysis covers the three LIBs required during the ship’s lifetime, whereby the retired batteries are all re-sold for second life usage. The used discount ratio r is 3% and costs and revenue are presented in present value. Over the lifetime of the vessel, the second-life use of batteries creates 20.8% of LIB capex gain compared to the alternative wherein the owner is retrofitting a LIB without utilizing the second life residual value of the retired LIB.

Fig. 5 illustrates the capital expenditure for 3 new LIBs during the lifetime of the vessel and shows the simultaneous forecasted revenue opportunity from second life LIB sales (residual value).

From Fig. 5, we can see that the decrease in the residual value of retired LIBs follows the general trend of declining LIB prices. However, as the relative value of retired LIBs remains at the same level, it has the potential to decrease the total investment cost of LIB retrofits significantly, i.e. we can understand that the overall kWh price of the battery retrofits will be lower.

As the economic forecast depends on actual price levels over the ship’s lifetime, we must estimate the potential variation of the results. Capex gain during the lifetime is ranging from 19.1% to 22.8%, whereby the highest LIB price forecast creates the highest gain. Fig. 6 depicts the used price forecast for marine batteries starting from the market price estimate for 2020.

From Fig. 6, we can see the three estimated marine battery price trajectories where the price erosion is high, moderate, or low. In the base case analysis, we use the moderate trajectory. Thus, if the battery prices would decrease according to the High trajectory, the value of the second life batteries would be the lowest as would be the residual value for the owner. If the battery prices are high, then there is more motivation to use second life batteries and the residual value would be consequently higher.

Second-life battery reuse is also studied based on EV batteries used in practical projects and from the technical and economic viability perspective: Zhu et al. indicate up to 60% of decrease in EV LIB costs by 2030 [26] Martinez-Laserna et al. indicate the battery upfront cost discount to be ca. 6–25% and total cost of ownership (TCO) reductions from 6% to 11% [15]. These results are in line with the estimates in this present study, even though our focus is on large (MWh scale) marine batteries.

4.1.3. Ship level LCC impact

This section examines the impact of the battery described above and its second-life use on the ship life cycle cost (LCC). The LCC for an electric ferry consists of ship level capital expenditure, annual operational expenses, and LIB-level annual costs. The total capex of the vessel in this case study and its accessories is 16,741,981 €. Fig. 7 shows the cost breakdown of the e-ferry capital expenditure.

As can be seen from Fig. 7, the share of the LIB in the upfront capex is 12.6%, indicating that the battery cost is not dominating, but it is, however, significant. This means that the second-life battery residual value has a positive impact on this portion of the total value. The follow up question is that how much life cycle cost reduction can we get from the efficient re-use of the batteries?

The life cycle cost also includes the annual operation cost of the ship, which is estimated for this case to be 1,711,670 € including crew costs, energy costs, maintenance costs, insurances, and other costs [6]. Over the vessel life of 36 years, the net present value of LCC is 54,927,996 €, when retrofit specific battery disassembly and disposal costs are taken into account, but the second life residual value is not utilized. The disposal cost estimate is based on offer levels of 1–2.6 €/kWh, which results in present cost of 180,274 € over the lifetime of the vessel. Disassembly of the battery system with 100 racks and 840 modules is estimated to take 200 h with labour costs being 45 €/h (salary and statutory costs).

Table 2 depicts the LCC for different scenarios: LCC with disposal cost and LCC with reused residual value.

As can be seen from Table 2, the difference between the LIB disposal and LIB reuse alternatives is 702,719 €, which is referred to as the “LIB reuse gain”. This consists of 180,274 € of savings on disposal costs and the residual value of the retired LIBs, which is 522,445 €. This means that the alternative where the LIBs are reused and sold for second life purpose will decrease the ship-level LCC by 1.3% compared to the conventional disposal of the LIBs after first life. This estimated LCC reduction is to a certain extent lower than in the electric vehicle case in
Ref. [15], but this can be explained by the different capital expenditure cost structures of electric cars and ships. When comparing the LCC LIB reuse gain 702,719 € to LIB LCC/capex cost, the economic gain is 20.8%.

It will be also interesting to compare a fully electric ferry with a traditional diesel ferry [6]. The LCC comparison of 1) a modern diesel ferry, 2) a fully electric ferry with battery disposal cost and 3) finally an e-ferry with second-life battery re-use are presented in Fig. 8.

Fig. 8 shows that an electric ferry with LIB reuse provides the LCC cost benefit of 8.6 M€ compared to a modern diesel ferry of comparable size and capacity, in other words, the diesel ferry LCC is 15.9% higher over a lifetime of 36 years. On the vessel level, we see that the main LCC improvement has been achieved by changing the energy source from diesel to a fully electric drive train and electric energy. From the vessel LCC perspective the LIB re-use gain is not significant, but it still reduces

| Ship level LCC impact, NPV |
|---------------------------|
| LCC with disposal          | 54,979,676 €  |
| LCC with reuse             | 54,276,956 €  |
| LIB disposal cost          | 180,274 €     |
| LIB reuse gain             | 702,719 €     |
| LCC reuse gain %           | 1.3%          |
| Total LCC/capex            | 18,017,769 €  |
| LIB LCC/capex              | 3,382,788 €   |

Fig. 5. LIB capital expenditure and residual value over lifetime of ship.

Fig. 6. Marine LIB system cost trajectory for three proposed scenarios.

Fig. 7. Capital expenditure of the fully electric ferry in this case study.

Table 2

The impact of re-use of the LIB on ship LCC.

| Ship level LCC impact, NPV |
|---------------------------|
| LCC with disposal          | 54,979,676 €  |
| LCC with reuse             | 54,276,956 €  |
| LIB disposal cost          | 180,274 €     |
| LIB reuse gain             | 702,719 €     |
| LCC reuse gain %           | 1.3%          |
| Total LCC/capex            | 18,017,769 €  |
| LIB LCC/capex              | 3,382,788 €   |

Fig. 8. Ship life-cycle cost calculation over 36 years for 2 different e-ferry cases and a diesel ferry case.
the life-time cost by 1.3%. However, second-life re-use decreases the LIB net cost significantly, by ca. 35% at the retrofit time. In the case of EVs, Martínez-Laserna et al. found that second life use allows upfront cost discounts up to 25% [15]. These discount levels will presumably be interesting to marine and ground transport EV owners.

4.2. Sensitivity scenarios

The used assumptions may be influenced by the development of the LIB industry as well as the evolution of recycling and re-purposing industries. The development will be significant since the massive volume increase of LIBs will lead to highly automated lines and facilities that produce tens of GWh of batteries each year. This will also require similar capacity levels from recycling and re-purposing lines. Simultaneously, battery chemistries and performance are evolving both in terms of cost and performance. However, the LIB market is divided to high volume and lower volume market segments and systems, so pricing is not directly comparable between application segments. In addition, discount ratio assumptions over time have an impact on the results.

4.2.1. Marine LIB price evolution

Assumptions about the LIB pricing for the marine industry are forecasted based on the latest market data and publications. Marine LIB pricing does not follow high volume EV batteries, but it is closer to the price trajectories of stationary storage, although pricing is somewhat higher due to the special functional and safety requirements. Market pricing in 2020 is factual and identical for all trajectories. Price erosion for high, moderate, and low forecasts exhibit a 26%, 33%, and 40% drop in 10 years (respectively), which is depicted in Fig. 6 and gathered in a numerical format in Table 3.

4.2.2. Discount ratio

Assumptions about the discount ratio also have a large impact on the results. In this study, we assume \( r = 3\% \), resulting in a 20.8% capex gain from second-life use over the ship’s lifetime. Assuming a discount ratio of 3%–6%, the LIB capex gain would vary between 20.8% and 14.6%.

4.2.3. Second-life battery pricing

According to this scenario, all LIB packs in marine applications can be used in stationary storage applications after their end of life in transport battery usage. Due to the valuable and useable raw materials in LIBs, the use of low-cost repurposed second-life batteries makes economic sense. In this scenario the re-selling price of a repurposed second-life battery was estimated to be 50% of the price of a new battery. However, the evolution of the second-life battery market and industry is in an early stage. Sensitivity of economic gains to the variation of second-life LIB price is estimated in Table 4, where range of second-life LIB price varies between 30% and 70% compared to new battery prices.

As can be seen from Table 4, even if second-life battery pricing would vary significantly, there would still be sensible economical gains available for owners and this effect is expected to become more dominant in the following years. It can be concluded that economic viability can be achieved for the second life battery circular economy concept, but it requires efficient processes and eco-design [43] to minimize the costs of refurbishment.

5. Conclusions

This work aims to clarify and quantify the economic opportunities arising from the application of circular economy to energy storage, with a special focus on the marine sector. To this end, a mathematical framework is proposed for economic evaluation which considers LIB-related circular economy aspects. At the EOL of the primary usage of a marine battery, there is still a residual value and capacity in the LIB, which can be used in other types of applications with lower performance requirements, representing a significant earning opportunity. On the other hand, material circulation is also important from an environmental aspect—when we can re-use products for several additional years, we can avoid unnecessary mining of virgin materials. Additionally, we avoid energy consumption for the unnecessary production of new cells and LIB parts along with the transportation of these materials. Finally, high volume LIB re-purposing for second life can itself become a significant business opportunity and revenue stream that creates new local jobs and simultaneously increases environmental sustainability of the battery industry ecosystem.

The continued strong growth of LIB use in electric vehicles in ground transport, stationary systems, marine systems, and consumer electronics indicates that both battery manufacturing and also material circulation and re-use industries will grow strongly in the coming decades. As processes become more efficient and automated, it is forecasted that the prices will decrease. However, as LIB technology requires scarce raw materials, it is assumed that strongly increasing volumes will not pull LIB prices to remarkably low levels. Therefore, market interest for re-use and recycling of the materials will remain high. In addition, it is good to bear in mind that tightening regulation pushes towards strong circular material flows. This article presents a quantitative assessment of the economic gains available in the marine sector from LIB-related material circulation.

This study has shown that the circular economy, and particularly the reuse of LIBs, may bring ca. 20% LCC cost savings and upfront retrofit discount of ca. 35% for the shipowner. To develop the circular economy of batteries, further research and development is needed to measure the performance and remaining life of retired batteries, so that the process of repurposing them is efficient, economical and resale is both reliable and enables safe usage. This is essential for discovering steps towards a profitable industry of second-life batteries.

In a broader sense, holistic and efficiently planned and regulated LIB circular material flows enable win-win-win situation from economic, environmental, and societal perspectives. This requires continuous and determined co-operation from whole ecosystem including designers, manufacturers, distributors, users, owners, regulators, and authorities.

| Table 3 | Marine LIB system cost trajectories, adapted from [3,38]. |
|---------|-----------------|-----------------|-----------------|-----------------|
|         | 2020            | 2030            | 2040            | 2050            |
| [$/kWh] | High            | Moderate        | Low             |                 |
|         | 490             | 323             | 268             |                 |
|         | 294             | 213             | 198             |                 |
|         | 176             | 140             |                 |                 |

| Table 4 | Sensitivity of results for second life battery pricing. |
|---------|--------------------------------------------------------|
|         | Second-life LIB price range | 30% | 50% | 70% |
|         | Retrofit capex gain % | 18% | 35.0% | 55% |
|         | LCC capex gain % (NPV) | 12% | 20.8% | 29% |


cRediT authorship contribution statement

Mika Lehmusto: Conceptualization, Methodology, Visualization, Formal analysis, Writing – original draft. Annukka Santasalo-Aarnio: Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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