VESSEL ADVANCED CLUSTERED AND COORDINATED ENERGY STORAGE SYSTEMS

Multidisciplinary approach to accelerate the development of innovative energy storage systems to complement batteries for zero-emission vessels.

D4.1 LCA methodology for on board energy storage systems

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Contributors		**Reviewers**	Salvatore D'Arco (Sintef Energy Research)

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1 Executive summary

The present report constitutes the deliverable D4.1 “LCA methodology for on board energy storage systems”, a document produced in the framework of WP4 “Techno-Economic and Environmental assessment against BESS”, Task. 4.1: “Assessment of environmental impact”. The report consists of three main parts. The first one consists of a literature review on the Life Cycle Assessment (LCA) studies on batteries, supercapacitors, and superconducting magnetic energy storage systems (in the following BESS, SuperCaps and SMES, respectively) in marine applications. The literature analysis was performed to identify how the main methodological aspects of the LCA were addressed in the available studies. The second part concerns the analysis of the available technical LCA guidelines (like as, for example, the European Commission Product Environmental Footprint Category rules PEFCR), on the industrial sector connected to the technologies proposed within the V-ACCESS project (e.g., batteries, naval sector). Finally, in the third part, a detailed guideline for conducting LCAs on the investigated ESSs implemented in marine applications is proposed. The guideline was drawn up in order to be compliant with the international standards ISO 14040 [1] and ISO 14044 [2]. Other methodological references were the “International Reference Life Cycle Data System” (ILCD) manual of the Joint Research Centre – JRC [3] and the recommendations of the European Commission relating to the use of common methodologies to measure and communicate the environmental performance of the life cycle of products and organizations [4], [5]. The guideline was developed according to the methodological phases that characterize a LCA study in accordance with the reference standards already mentioned. The guideline presented in this deliverable is based on international standards and on the specific literature. In the final version of D4.1, the guideline will be updated based on the results of the LCA applied to V-ACCESS case studies.

2 Introduction

This deliverable is divided into the following sections:

- Section 2 defines abbreviations and acronyms used in this report.
- Section 3 analyse the LCA studies on BESS, SuperCaps and SMES implemented in electric vessel, when available.
- Section 4 analysis of the available technical LCA guidelines on relevant connected industrial sectors.
- Section 5 presents a detailed guideline to conduct LCA of the investigated ESSs in marine applications. This guideline was developed according to the methodological phases that characterize a LCA study in accordance with the reference standards ISO 14040 [1] and ISO 14044 [2].

3 Abbreviations and acronyms

BESS	Battery energy storage system
CFB-EV	Carbon Footprint of Electric Vehicles Batteries
EEPS	Electronic and Electrical Products and Systems
EoL	End of Life

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ESS	Energy Storage System
EV	Electric Vehicles
FU	Functional Unit
GBA	Global Battery Alliance
HMA	Harmonized Market Approach
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
PCR	Product Category Rules
PEFCR	Product Environmental Footprint Category Rules
PKT	Person Kilometre Travelled
PMA	Physically Modelled Approach
PSR	Product Specific Rules
SMES	Superconducting Magnetic Energy Storage
UPS	Uninterruptible Power Systems
V-ACCESS	Vessel Advanced Clustered and Coordinated Energy Storage Systems

4 Literature analysis

4.1 Research method and assessed documents

In order to identify and select the studies to be analysed, a specific literature research scheme was adopted through the selection of international search databases, designated keywords, as well as general and specific eligibility criteria.

The literature review was accomplished by searching in ScienceDirect, Scopus and Google Scholar using keywords like as “LCA”, “Life cycle assessment”, “lifecycle”, and “ship”, “vessel”, “boat”, and “electric”, “propulsion”, “powered”. In addition, the general eligibility criterion to include only documents in English language was selected. With the defined research method, 148 documents were identified. The number of documents were further refined through a comprehensive abstract analysis and specific eligibility criteria to include only papers related to marine application case studies in which the environmental impacts were estimated through the LCA approach. According to this further analysis eighteen documents were suitable for the current literature review: seventeen regarding LCAs of battery powered ship, one reports an LCA of an electric marine vessel equipped with a supercapacitor, while for SMES there were no available studies in marine application field. For BESS only LCA in marine application were selected, excluding papers that analyse batteries in other contexts (e.g., automotive use). LCA of SMES and SuperCaps were considered when dealing with other applications. In addition, analysis was extended to include also documents classified as grey literature.

According to these criteria, seventeen documents related to BESS (16 papers published in peer-reviewed scientific journals and one master thesis), one related to SuperCaps (published in peer-reviewed scientific journal) and one related to SMES (published in peer-reviewed scientific journal) were suitable for the current literature review. However, in addition to the papers selected based on the eligibility criteria, 3 additional papers on SuperCaps [6] [7] [8] and one on SMES [9] have been added. Even if these papers do not apply the LCA methodology, they have been included in the analysis since they carry out an environmental assessment of these ESSs which could provide useful information for the application of the LCA to the case studies selected within the V-ACCESS project. The selected documents were published between 2000 and 2023. Table 1 shows the main characteristics of the analysed case studies on BESS, SuperCaps and SMES in the available applications.

In the following sections the results obtained through systematic analysis are presented with reference to the main aspects related to application of the LCA method (e.g., functional unit (FU), system boundaries, inventory data, impact assessment method, etc.).

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TABLE 1 – DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW

Reference	Title	Year	Type of document	Marine application	Ship type	Technology/Power system
Chin-Ling, J., Roskilly, A.P. [10]	Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study	2016	Journal paper	X	Roll on/roll off cargo ship	Hybrid power system: 6 diesel gensets plus cold-ironing, PV, and lithium-ion battery systems
Maritime Battery Forum [11]	Life cycle analysis of batteries in maritime sector	2016	Report	X	Platform Supply Vessel (PSV) Short rout ferry	PSV: 4-generator diesel electric propulsion system PSV: 4-generator diesel electric propulsion system plus battery as spinning reserve Ferry: diesel electric (2 generator sets) Ferry: full electric (battery)
Espen Nordtveit [12]	Life Cycle Assessment of a Battery Passenger Ferry	2017	Master thesis	X	Passenger ferry	Battery
Jeong, B., et al. [13]	An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems	2018	Journal paper	X	Short-route ferry (Ro-Pax ferry)	Hybrid power system: diesel electric system consisting of three 360kW diesel generators used to drive the electric motors connected to the propulsion systems and of two sets of lithium-ion batteries which can share the electric loads with the onboard diesel engines
Jeong, B., et al. [14]	Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity	2020	Journal paper	X	Roll on/roll off (ro-ro) passenger ship	Battery: Lithium-ion batteries (Battery capacity: 830 kWh)
Perčić, M., et al. [15]	Life-Cycle Cost Assessment of Alternative Marine Fuels to Reduce the Carbon Footprint in Short-Sea Shipping: A Case Study of Croatia	2020	Journal paper	X	Ro-Ro passenger ferries: very short (ship1), medium (ship 2) and relative long route (ship3)	Diesel-powered ship (reference scenario), electric-powered ship (NMC Li-ion battery), methanol-powered ship, Dimethyl Ether-powered ship, natural gas-powered ship, hydrogen-powered ship, soybean-biodiesel-diesel blend B20-powered ship.
Perčić, M., et al. [16]	Life-cycle cost assessments of different power system configurations	2020	Journal paper	X	Roll-On-Roll-Off-Passenger passenger vessel operating in	Lithium-ion battery

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	to reduce the carbon footprint in the Croatian short-sea shipping sector				short-sea shipping sector	
Wang H., et al. [17]	Life cycle analysis and cost assessment of a battery powered ferry	2021	Journal paper	X	Fast catamaran ferry	$LiNiMnCoO_2$ battery
Fan et al. [18]	Decarbonising inland ship power system: Alternative solution and assessment method	2021	Journal paper	X	Inland ships (Canal ship consisting of a 64 TEU container ship and river ship consisting of a 6700 ton bulk carrier)	Battery energy storage system consisting of two containerised Lithium-Ion battery packs, each of which can provide 1080 kWh (for the canal ship). Hybrid power consisting of two LNG generators, one battery pack, and two 'one-out, two-in' gearboxes (for the river ship)
Perčić, M., et al. [19]	Electrification of Inland Waterway Ships Considering Power System Lifetime Emissions and Costs	2021	Journal paper	X	Inland ships: cargo ship, passenger ship, and dredger	Diesel engine powered ship configuration (reference scenario) and two Li-ion battery-powered ship configurations (with and without a photovoltaic system)
Perčić, M., et al. [20]	Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation	2022	Journal paper	X	Ro-Ro passenger ferry, very short (ship1), medium (ship 2) and relative long route (ship3)	Pb-acid, Ni-MH, and Lithium-ion battery technologies
Park, C., et al. [21]	Live-Life cycle assessment of the electric propulsion ship using solar PV	2022	Journal paper	X	RoPax ferry	Case1: Diesel-electric operation Case2: Full battery mode Case3: Full battery with a solar PV system
Kim, S., et al. [22]	Lifecycle Environmental Benefits with a Hybrid Electric Propulsion System Using a Control Algorithm for Fishing Boats in Korea	2022	Journal paper	X	Fishing boats (4.99 ton, 9.77 ton, and 47 ton)	Battery hybrid system that uses both an engine and a battery
Kanchiralla, et al. [23]	Life-Cycle Assessment and Costing of Fuels and Propulsion Systems	2022	Journal paper	X	Roll-On-Roll-Off-Passenger (RoPax) vessel	Battery
Jeong, B., et al. [24]	Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole?	2022	Journal paper	X	Short-route ferries	Battery
Park, C., et al. [25]	Lifecycle energy solution of the electric propulsion ship with Live-Life	2022	Journal paper	X	Hybrid Ro-Pax ferry	Case1: Electric propulsion ship with Diesel generator engine

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	cycle assessment for clean maritime economy					Case2: Electric propulsion ship with Hybrid power sources Case3: Electric propulsion ship with Full battery Case 4: Electric propulsion ship with Battery and Solar PV system Case5: Electric propulsion ship with Hydrogen fuel cell. Case6: Electric propulsion ship with Hydrogen fuel cell and Battery Case7: Electric propulsion ship with Hydrogen fuel cell, Battery, and Solar PV system Case8: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell Case9: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell and Battery. Case10: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell, Battery, and Solar PV system
Guven, D., Kayalica, M.O. [26]	Life-cycle assessment and life-cycle cost assessment of lithium-ion batteries for passenger ferry	2023	Journal paper	X	Passenger ferry	Lithium-ion batteries (NMC532, NMC622, NMC811, NCA, LFP)
Kamiya, S., et al. [27]	Life Cycle Assessment and Economical Evaluation of Superconducting Magnetic Energy Storage Systems in a Power System	2000	Journal paper	-	-	SMES (Storage energy 5 GWh, maximum output 1 GW, rated current 707 kA, maximum voltage 3.6 kV)
Hartikainen,T., et al. [9]	Environmental advantages of superconducting devices in distributed electricity-generation	2007	Journal paper	-	-	SMES
Conte, M., et al. [6]	Hybrid battery-supercapacitor storage for an electric forklift: a life-cycle cost assessment	2014	Journal paper	-	-	SuperCaps (Combined power system: supercapacitors plus lead-acid batteries)
Manouchehrinia, B., et al. [7]	Emission and life cycle analysis of hybrid and pure electric propulsion systems for fishing boats	2018	Journal paper	X	Lobster fishing vessels	SuperCaps
Jiang, Z., et al. [28]	Environmental life cycle assessment of supercapacitor electrode	2021	Journal paper	-		SuperCaps

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	production using algae derived biochar aerogel					
Citalingam, K. and Go, Y. L. [8]	Hybrid energy storage design and dispatch strategy evaluation with sensitivity analysis: techno-economic environmental assessment	2022	Journal paper	-		SuperCaps

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4.2 Goal and scope definition

The goal definition is the first phase of any LCA and determines the purpose of the study in detail. The scope definition describes what product systems are to be assessed and how this assessment should be developed. In detail, the scope definition regards the identification of the following items: functions provided by the examined product system, FU, system boundaries, impact categories and life cycle impact assessment methods, possible approach to solve multifunctionality (e.g., allocation procedures) and cut-off rules. In the present paragraph, we analyse the main methodological choices made by different authors for this relevant part of an LCA study.

4.2.1 Investigated system: type of ship and power systems

Concerning the investigated system, the state-of-the-art analysis highlighted that Roll-On-Roll-Off (Ro-Ro) and ferry passenger ships were the most widely investigated products among the available LCA studies, while Lithium-ion battery was the most adopted energy storage technology, in the LCAs in which the battery chemistry is specified (Table 1), for the hybrid or full electric power systems. In detail, Jeong, B. et al. [13] analysed a Ro-Pax ferry with a hybrid power system consisting of three 360 kW diesel generators used to drive the electric motors connected to the propulsion systems and two sets of lithium-ion batteries. In another study, Jeong, B. et al. [14] focused on a fully Lithium-ion battery-power Ro-Pax ferry. Perčić, M., et al. performed LCA studies on Roll-On-Roll-Off- passenger vessel and on passenger ship operating in short-sea shipping sector in which the battery energy storage system is based on the Li-ion technology [15] [16] [19] [20]. In addition, in Perčić, M. et al. [20] also the Pb-acid and Ni-MH battery technologies were investigated.

Other case studies regard a platform supply vessel [11], a dredger [19], two cargo ships [10] [19], a fast catamaran ferry [17] and three fishing boats [22]. Particularly, the Maritime Battery Forum perform an LCA study on a platform supply vessel equipped with 4-generator diesel electric propulsion system and a battery as spinning reserve. Perčić, M., et al. [19] analysed a dredger with a battery sized to allow it to operate for 8 h without recharging. Chin-Ling and Roskilly [10] chose RoRo cargo ships as the reference ship equipped with a hybrid power system involving 6 diesel gensets (prime movers), a PV system, four phosphate graphite lithium-ion batteries. In addition, a cold-ironing supplies power from on-shore network when the ship was in port. The fast catamaran ferry case study is equipped with a Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) battery [17]. Kim, S., et al. [22] analysed three fishing boats (4.99 ton, 9.77 ton, and 47 ton) in which the propulsion system uses both an engine and a battery.

4.2.2 Goal, function, and functional unit (FU)

To highlight how the methodological aspect of selecting the FU is particularly connected to the goal of the LCA and to the main functions provided by the product system, in this paragraph these aspects are analysed together.

The goal definition generally contains reasons for carrying out the study, the intended applications of the results and the target audience [1]. This significantly influences the LCA because decisions made in later LCA phases must be consistent with the goal definition [29]. The purpose of an LCA is to estimate the environmental impacts of options for fulfilling a certain function. Function is very important to understand when comparing two or more product systems because a comparison is only meaningful if the compared systems provide the same function. An LCA study should, thus, first clearly define the investigated system and the functions it delivers.

The functional unit (FU) is a key concept in LCA methodology, and it is closely associated with the identified function. It defines the quantification of the identified function (performance characteristics) of the product system. Its purpose is to provide a reference to which the input and output flows of the product system are related. This reference is necessary in comparative LCAs to ensure that the comparison of different systems providing the same function is made on a common basis. When defining the functional unit, it is important to ensure it is clear, measurable, representative of the product's intended use, and consistent with the goal and scope of the LCA study [1], [2].

TABLE 2 resumes the goals and the FUs identified in the examined LCAs. Concerning the goal definition, from the literature analysis results that the examined LCAs were mainly oriented to a comparative assessment, e.g., aimed at investigating if the electric propulsion is a better solution compared to conventional diesel combustion engines from the environmental sustainability point of view. Moreover, the function provided by the examined system was generally clearly described. Regarding the choice of the functional unit, the analysis highlighted a wide variability among the examined studies and several LCAs in which the FU was not clearly declared or was not correctly defined (TABLE 2). For the studies aimed at comparing the electric propulsion versus the conventional diesel one, the FU are mainly based on a specific operational time, e.g., ten years' ship operation [11], annual energy consumption per ship operational year [17]. However, among the seventeen LCA studies on full battery powered ship and/or hybrid battery powered vessels only six selected and clearly declared an appropriate FU coherent with the LCA goal.

TABLE 2 – GOALS AND FUNCTIONAL UNITS OF THE DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW

Reference	Goal	Functional unit
Chin-Ling, J., Roskilly, A.P. [10]	To assess the environmental impact of a new-build hybrid system (which incorporated advanced technologies such as cold-ironing, photovoltaic (PV) and lithium-ion battery systems) proposed for RoRo cargo ships which would be travelled within Emission Control Areas with frequent port calls.	The operation of the hybrid power system implemented onboard a RoRo cargo ship travelling on regular routes within Emission Control Areas (ECAs) over a lifespan of 30 years
Maritime Battery Forum [11]	To compare the environmental impacts associated to a hybrid platform supply vessel (PSV equipped with diesel generators and battery) and to a fully electric ferry with non-hybrid PSV and a diesel electric ferry, respectively	Ten years' ship operation
Espen Nordtveit [12]	To investigate if electric propulsion in high-speed passenger ferries is a better solution compared to conventional diesel combustion engines, with respect to the environmental impacts.	Person kilometre travelled (PKT)
Jeong, B., et al. [13]	To investigate the advantages of battery usage comparing a hybrid propulsion system to conventional diesel-electric (DE) and diesel-mechanical (DM) ones for a short-route ferry	The FU is not explicitly stated. The FU should be the whole ship operation time (lifetime is in the range of 0-31 years. 0: construction stage, 1 to 30: for operation and maintenance, and 31: for scrapping stage
Jeong, B., et al. [14]	To investigate the holistic environmental benefits of using a battery system on a roll on/roll off (ro-ro) passenger ship which was originally fitted with a diesel engine engaged in Korean coastal service.	The FU is not explicitly stated. From the analysis of the paper the FU should be "The energy sources consumed by the case ship in consideration".

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Perčić, M., et al. [15]	To investigate the environmental impact of different ship power systems, focusing only on GHG emissions, i.e., the Carbon footprint, released during the ship lifetime of 20 years.	The FU was not correctly defined. Carbon Footprint of the power system configuration released during the ship lifetime (20 years) and is presented in tons of CO_{2eq}.
Perčić, M., et al. [16]	To identify the most environmental and economical solution for retrofitting a ro-ro passenger ship engaged in shortsea shipping in the Croatian part of the Adriatic Sea.	The FU is not explicitly stated. From the analysis of the paper, it emerges that the UF is 1 nautical mile.
Wang H., et al. [17]	To perform an LCA for a battery-powered ferry for comparing the performances of conventional marine engines and innovative battery power plants to quantify the benefits of replacing marine diesel engines and generator sets with a battery system and electric motors.	Annual energy consumption per ship operational year (for engine power system it is linked to the fuel consumption and in a battery power system it is related to electricity used; all over the ship life span, all the phased and activities can be connected or converted by considering this functional unit). The ferry will be operated 18 h per day and 320 days per year for a life span of 30 years. Each round trip will last 3.6 h and the idling time at destinations will be about 0.35 h (21 min).
Fan et al. [18]	To investigate strategies for decarbonising inland ship power systems comparing a diesel engine-powered solution and battery-powered solution	Not clearly specified. It seems that the impacts are referred to the lifetime mileage
Perčić, M., et al. [19]	To set a model for investigation of the applicability of different power system configurations both from the environmental and economic point of view for the retrofit of three different vessel types	Ship lifetime mileage
Perčić, M., et al. [20]	To compare the conventional power system with a diesel engine and alternative power system with a selected battery to identify convenient technology for zero-emission shipping according to the environmental and economic criteria.	The FU was not correctly defined. The amount of emissions over the ship lifetime, which is set at 20 years. (Impacts presented as FU)
Park, C., et al. [21]	To estimate the holistic environmental benefits/harms of PV electric ships under various operating scenarios.	Not clearly specified. It seems that authors consider environmental impacts as FU.
Kim, S., et al. [22]	To investigate total carbon dioxide emissions through fuel consumption of three (4.99 ton, 9.77 ton, and 47 ton) representative fishing boats.	Not clearly specified. It seems that authors consider environmental impacts as FU.
Kanchiralla, et al. [23]	To investigate the different overall energy conversion, environmental performance, and economic conditions over the entire life cycle of eight decarbonization solutions for Roll-On-Roll-Off-Passenger (RoPax) vessel.	One round trip from Gothenburg to Kiel and back with the case study ship.
Jeong, B., et al. [24]	To determine whether battery-powered vessels are ultimately a cleaner option over conventional diesel ships.	Not clearly specified. It seems that authors consider environmental impacts as FU.
Park, C., et al. [25]	To compare three zero-carbon fuels: ammonia, hydrogen, and inland electricity through a life cycle approach.	Not defined
Guven, D., Kayalica, M.O. [26]	To investigate the environmental impacts of different lithium-ion battery-powered and diesel-powered ferries. The scope is restricted to six lithium-ion battery types and three marine diesel oils.	The FU is not explicitly stated. From the analysis of the paper the FU should be "The operational profile of the selected ferry throughout its lifetime".
Kamiya, S., et al. [27]	To assess the introduction of SMES into a power system and its effects in terms of energy and environmental issues.	Not defined

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Hartikainen,T., et al. [9]	To assess the environmental benefits of superconducting machinery by comparing suitable devices with their competitors in distributed generation networks	An electricity storage system with a power rating of 50 kW, a storage capacity for 450 kWh and an average delivery of 150 kW h electrical energy per day for 20 years. (Not LCA study)
Conte, M., et al. [6]	The effective technical and economic benefits of Electrochemical Capacitors integration (theoretically and experimentally) of a conventional electric forklift.	Not defined (Not LCA study)
Manouchehrinia, B., et al. [7]	To compare the hybrid electric and pure electric propulsion system designs for lobster fishing boats studied based on infield acquired operation data.	1 trip of 6 hours (Not LCA study)
Jiang, Z., et al. [28]	To compare the environmental performances of nitrogen-doped biochar aerogel-based electrode (BA-electrode) production and graphene oxide aerogel-based electrode (GOA-electrode) production. Hotspot life cycle stages for each assessed environmental impact/damage category and each technology, and the environmental improvement potentials were also identified.	A supercapacitor with capacitance of 5 F
Citalingam, K. and Go, Y. L. [8]	To develop an optimized hybrid energy storage system utilizing battery and supercapacitors to complement a large-scale solar PV system	Amount of energy that cycles through the storage bank (within 3 different scenarios) in 1 year (Not LCA study)

In detail, Chin-Ling and Roskilly [10] conducted an LCA study to assess the environmental impact of a new-build hybrid system proposed for RoRo cargo ships. Its application was to support research development on the selected emerging marine system. The function of the product system was to supply power to all consumers onboard a RoRo cargo ship for 30 years and, consequently, the operation of the hybrid power system implemented onboard a RoRo cargo ship travelling on regular routes within Emission Control Areas (ECAs) over a lifespan of 30 years was selected as FU. The Maritime Battery Forum [11] analysed two different case studies with the aim to compare ships using batteries to ships without batteries. The environmental performance of a PSV operating with a 4-generator diesel electric propulsion system (non-hybrid case) was compared with a PSV which employs a battery as spinning reserve (hybrid case), while a diesel electric ferry was compared to a fully electric ferry. Ten years' ship operation is the FU chosen in the work [11] for both case studies. Espen Nordtveit [12] performed an LCA with the aim to investigate if electric propulsion in high-speed passenger ferries is a better solution compared to conventional diesel combustion engines, with respect to the environmental impacts. The person kilometre travelled (PKT) was selected as FU. The PKT was calculated based on the average Norwegian capacity utilization in buses as shown in the Equation 1:

$$PKT: total\ travelled\ km\ per\ lifetime \times Person\ capacity \times capacity\ utilization \qquad (1)$$

Where, the person capacity is the maximum number of persons that can travel with the public transportation technology, the capacity utilization is the ratio between the passenger-km with bus, boat and train and the seat-km.

Jeong, B. et al. [13] compared a hybrid propulsion system to conventional diesel-electric (DE) and diesel-mechanical (DM) ones for a short-route ferry. The FU was not clearly declared. The analysis of the paper highlighted that the FU should be the ship operating in the range of 0 - 31 years (0 is

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the construction stage, 1 to 30 for operation and maintenance, and 31 for scrapping stage). Jeong, B. et al.[14] compared the environmental footprint of the diesel-mechanical and fully battery-powered vessels focusing on the life cycle of the energy sources consumed by the case ship in consideration. The FU, not explicitly stated, should be "the energy sources consumed by the case ship in consideration".
Perčić, M., et al. [15] performed an LCA with the aim to investigate and compare the environmental impact of different ship power systems including a fully electric battery powered ship, focusing only on GHG emissions, i.e., the carbon footprint (CF), released during the ship lifetime of 20 years. The FU is defined as "CF of the power system configuration released during the ship lifetime". The FU declared by authors is not in compliance with ISO 14040 where FU is defined as a "quantified performance of a product system for use as a reference unit" [1]. The same FU was selected by Perčić, M., et al. [20]. However, the analysis of the papers highlighted that the authors probably referred to the travelled lifetime milage.
Perčić, M., et al. [16] evaluated and compared the environmental impact of three different ship power systems (an existing diesel engine-powered solution and two potential battery-powered ship options with and without photovoltaic cells) as options for retrofitting Croatian ro-ro passenger ships. The FU was not explicitly declared; however, the life cycle impact results are referred to 1 nautical mile.
Wang, H. et al. [17] compare a marine diesel engines and generator sets propelled ferry with battery system and electric motors propelled ferry, the FU was the energy consumption per ship operational year.
Fan et al. [14] investigated strategies for decarbonising inland ship power systems comparing a diesel engine-powered solution and battery-powered solution. The FU is not clearly declared. The environmental impacts were reported with reference to the lifetime mileage.
Jeong et al. [24] investigate the holistic environmental benefits of using a battery system on a roll on/roll off (ro-ro) passenger ship which was originally fitted with a diesel engine. In this case the FU is the life cycle of the energy sources consumed by the case ship in consideration. Guven and Ozgur Kayalica [26] investigate the environmental impacts of different lithium-ion battery-powered and diesel-powered ferries considering as FU the operational profile of the selected ferry throughout its lifetime. The different overall energy conversion, environmental performance, and economic conditions over the entire life cycle of eight decarbonization solutions for Roll-On-Roll-Off-Passenger (RoPax) vessel was studied by Kanchiralla et al. [23] and FU was one round trip from Gothenburg to Kiel and back with the case study ship.

In the case of SuperCaps, from the four selected papers, only three selected an appropriate FU and for energy storage in maritime applications only one LCA study is available: Manouchehrinia et al. [7] present a study where hybrid and pure electric propulsion systems for fishing boats are considered and FU is one year ship operation (6 hours per day x 30 day per month x 6 months per year). The other three studies present applications in other industrial sectors: Citalingam and Go [8] develop an optimized hybrid energy storage system utilizing battery and supercapacitors to complement a large-scale solar PV system. FU is the amount of energy that cycles through the storage bank in 1 year. Supercapacitor electrode production process using algae derived biochar aerogel was studied by Jiang et al. [28] where FU is a supercapacitor with capacitance of 5 F.

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For SMES there are no available LCA studies in the maritime applications and, from the two considered documents in the current literature review, only one study presented an appropriate FU: Hartikainen et al. [9] presented Superconducting Magnetic devices in distributed electricity-generation considering as FU an electricity storage system with a power rating of 50 kW, a storage capacity for 450 kWh and an average delivery of 150 kWh electrical energy per day for 20 years.

4.2.3 System boundaries

System boundaries definition is a way to identify which processes within the entire life cycle of the involved systems need to be analysed or, to simplify the system, can be neglected. System boundaries define process phases that need to be included within the LCA and their choice must be consistent with the target of the study. Full boundaries should also define what was excluded, for example due to a lack of data, or data that is assumed negligible.

Cradle-to-grave is the full life cycle assessment from resource extraction ('cradle' = earth) to the use phase and disposal phase ('grave'). Cradle-to-gate is an assessment of a partial product life cycle from resource extraction to the factory gate (i.e., before it is transported to the consumer).

When LCA study deals with fuels, usually the term Well-to-Pump (WTP) is used, and it includes all operations from raw material extraction to the provision of fuel to customers. Well-to-Wake (WTW) instead, incorporates WTP, and output emissions produced throughout operation (i.e., Pump-to-Wake, PTW). Likewise, Well-to-wheel (WTW) is used to assess the LCA of fuels, it includes all phases of its life cycle, from the extraction of raw materials to their use. There are two components to the WTW assessment: Well-to-Tank (WTT) and Tank-To-Wheels (TTW). WTT includes the fuel production phases, and TTW the use of fuel.

In literature, the cradle-to-grave and cradle-to-gate (also as Well-to-Wake) perspectives are the most frequently employed. In some studies, system boundaries are not well defined, and in others more than one boundary system is considered (Table 3).

TABLE 3 –SYSTEM BOUNDARIES OF THE DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW

REF	System boundaries
Chin-Ling, J., Roskilly, A.P. [10]	Cradle-to-grave
Maritime Battery Forum [11]	Cradle-to-gate
Espen Nordtveit [12]	Cradle-to-grave (the environmental impact from the material extraction, material production and operation to its EoL is considered. The EoL treatment is not considered in the work)
Jeong, B., et al. [13]	Cradle to grave (construction, operation maintenance and scrapping)
Jeong, B., et al.[14]	Authors adopted the life cycle of energy pathways consisting of the production, the transport, and the use stages.
Perčić, M., et al. [15]	Well-to-wheel (since each power system configuration includes an engine (a diesel, dual-fuel, or electric engine) and total average ship power (P_{ave}) is equal for all the configurations, it is assumed that the environmental assessment of an engine for all considered configurations is the same as for the diesel engine)
Perčić, M., et al. [16]	Processes of raw material recovery, the production of a power source and its supply to the vessel are referred as “Well-to-Pump” (WTP), while WTP processes and the use of the power source in vessel operations are termed as “Well-to-Wheel” (WTW). Vehicle operations are referred to as “Pump-to-Wheel”, or, in the case of a ship, “Pump-to-Propeller”.

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Wang H., et al. [17]	Cradle-to-grave (scrap phase) stages in the battery life cycle
Fan et al. [18]	Well-to-Wake (Cradle-to-gate)
Perčić, M., et al. [19]	Well-to-Wake (Cradle-to-gate)
Perčić, M., et al. [20]	First phase: Well-to-Pump (WTP), it considers emissions released from the fuel cycle, which includes processes of raw material extraction, fuel production and its transportation to the refuelling station Second phase: Pump-to-Wake (PTW), it considers the emissions released during the use of fuel for ship operation Third phase: the manufacturing phase, and it considers emissions released from the manufacturing process of the main elements (battery, engine, etc.) of a power system diesel engine or electric engine are excluded from the environmental assessments due to the assumption that they contribute to air pollution in the same manner. Only batteries manufacturing processes are investigated.
Park, C., et al. [21]	Well-to-Wake
Kim, S., et al. [22]	Well-to-Tank and Tank-to-Wake
Kanchiralla, et al. [23]	Cradle-to-gate
Jeong, B., et al. [24]	Cradle-to-gate
Park, C., et al. [25]	Well-to-Wake
Guven, D., Kayalica, M.O. [26]	Well-to-Wake and Pump-to-Wake Disposal phase of batteries are not provided, the study was focused only on the material extraction and manufacturing phases, and operation of vessel.
Kamiya, S., et al. [27]	Not defined (Authors calculate the input energy for constructing the SMES (each element))
Hartikainen,T., et al. [9]	Not defined (Authors use SMES production statistics) (Not LCA study)
Conte, M., et al. [6]	Not defined (Not LCA study)
Manouchehrinia, B., et al. [7]	Not defined (Not LCA study)
Jiang, Z., et al. [28]	The supercapacitor fabrication process was not included in the study. BA-electrode technology, the impacts of EP collection on the sea, biochar aerogel production, and the transportation between these two stages were considered. The commercial GOA-electrode, the productions of graphite, graphene oxide, and GOA and the transportations linking stages were included. Same technical processes and materials/energy input for supercapacitor production were assumed. The only difference between technologies was the input amount of carbon aerogel-based electrode needed for per-unit supercapacitor production.
Citalingam, K. and Go, Y. L. [8]	Not defined (Not LCA study)

4.2.4 Approach to solve multifunctionality

A process is multifunctional when it provides more than one product output and/or provides more than one service [29]. Multifunctional processes constitute a methodological challenge in LCA, which is based on the idea of analysing individual product systems based on the primary functions they provide to determine the environmental impact from the product. To solve multifunctionality, the ISO 14044 provides the following hierarchy of solutions: (1) Subdivision of Unit Process; (2) System Expansion; (3) Allocation (for more detail see Paragraph 6.1).

In the examined literature studies, no need to solve multifunctionality emerged. The only example is represented by Chin-Ling and Roskilly [10] which declared to apply the system expansion approach to consider the replacement of that components of the product system characterized by a shorter lifetime compared to the analysed timeframe (30 years). However, this case did not represent a multifunctional process example.

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4.2.5 Cut-off rules

Cut-off rules define material or energy flows, associated with the process unit, which are excluded from the study because their impacts are retained negligible. In the current literature review, all studies do not use cut-off rules, or it is not possible to deduce from studies the following criteria. The only exception is represented by Jeong, B., et al. [10] which excluded from the analysis the battery and the diesel engine manufacturing, installing, and recycling processes since a series of previous LCA studies have proven that their environmental impacts to be negligibly small.

4.2.6 Impact Categories and Methods

Impact categories selection must be reliable with the target of the study, categories choice must be complete and should cover all the main environmental issues related to the system. To compare results from different studies, it is absolutely needed that studies use the same impact categories and the same impact method for their quantification. In the current report, twelve studies do not specify the used method, seven considered CML method and three the ReCiPe method (Table 4). One author considered three different methods: CML, ILCD and Eco-Indicator99 [10]. The most used impact category is Global Warming Potential (eighteen studies out of twenty-three), and three studies use the 18 mid-point impact categories of ReCiPe method (Table 4).

TABLE 4 –IMPACT CATEGORIES AND METHODS OF THE DOCUMENTS ANALYZED WITHIN THE BIBLIOGRAPHIC REVIEW

REF	Impact Categories	Method(s)
Chin-Ling, J., Roskilly, A.P. [10]	Abiotic Depletion of Elements, Terrestric Ecotoxicity, Photochemical Ozone Creation Potential, Eutrophication Potential, Abiotic Depletion of Fossil, Acidification Potential, Human Toxicity Potential, Freshwater Aquatic Ecotoxicity Potential, Global Warming Potential, Marine Aquatic Ecotoxicity Potential	CML 2001
	Resource Depletion, Fossil and Mineral, Marine Eutrophication, PM / Respiratory Inorganics, RiskPoll, Total Freshwater Consumption, Including Rainwater, Photochemical Ozone Formation, Acidification, Terrestrial Eutrophication, IPCC Global Warming, Ecotoxicity for Aquatic Freshwater	ILCD
	Human Health, Climate Change, Human Health – Respiratory, Ecosystem Quality – Land-Use, Resources – Fossil Fuels, Resources – Minerals, Ecosystem Quality – Ecotoxicity, Ecosystem Quality– Acidification/Nutrification	Eco-Indicator99
Maritime Battery Forum [11]	Global warming potential	ReCiPe hierarchical method
Espen Nordtveit [12]	18 midpoint impact categories	ReCiPe
Jeong, B., et al. [13]	Global warming potential, Acidification potential, eutrophication potential and photochemical ozone creation potential.	CML 2016 model
Jeong, B., et al.[14]	Global warming potential, Acidification, Eutrophication potential, Photochemical ozone creation potential	CML 2001
Perčić, M., et al. [15]	Global warming potential	Not specified (It seems the database Greet 2019; authors use the FC IPCC 2006)

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Perčić, M., et al. [16]	Global warming potential	Not specified (It seems the database Greet 2019; authors use the FC IPCC 2006)
Wang H., et al. [17]	Global warming potential	CML-IA baseline
Fan et al. [18]	Life-cycle carbon emissions (tCO2)	Not specified
Perčić, M., et al. [19]	Global warming potential	Not specified (It seems the database Greet 2019; authors use the FC IPCC 2006)
Perčić, M., et al. [20]	Global warming potential	Not specified (It seems the database Greet 2019; authors use the FC IPCC 2006)
Park, C., et al. [21]	Global warming potential, acidification potential, eutrophication potential, and photochemical ozone creation potential	CML 2001
Kim, S., et al. [22]	Global warming potential, acidification potential, eutrophication potential, and photochemical ozone creation potential	CML 2001
Kanchiralla, et al. [23]	Acidification; human toxicity, cancer effects; global warming potential (GWP20 and GWP100); human toxicity, noncancer effects; ecotoxicity freshwater; ozone depletion; eutrophication marine; particulate matter; eutrophication terrestrial; photochemical ozone formation.	Authors refer to "Zampori, L.; Pant, R. Suggestions for Updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications Office of the European Union: Luxembourg; 2019. DOI:10.2760/265244.
Jeong, B., et al. [24]	Global warming potential, Acidification potential, Eutrophication potential and Photochemical Ozone creation potential	Not specified
Park, C., et al. [25]	Global warming potential	Not clear, maybe CML, authors refer to a previous study (Park, C., et al. [21]) that uses CML
Guven, D., Kayalica, M.O. [26]	Global warming potential, NOx and SOx emissions, particulate matter emissions, and energy and water consumption.	GREET 2021
Kamiya, S., et al. [27]	CO_2 emissions	Not specified
Hartikainen,T., et al. [9]	Greenhouse-gas emissions in g(CO2-eq)/kWh	Not specified (Not LCA study)
Conte, M., et al. [6]	Not specified	Not specified (Not LCA study)
Manouchehrinia, B., et al. [7]	Global warming potential	Not specified (Not LCA study)
Jiang, Z., et al. [28]	Eighteen impact categories and Damage categories: Human health and Ecosystems	ReCiPe 2016
Citalingam, K. and Go, Y. L. [8]	Emission rate of three greenhouse gasses: carbon dioxide (CO2), sulphur dioxide (SO2), and nitrogen oxide (NOx)	Not specified (Not LCA study)

4.3 Lifecycle Inventory (LCI)

The inventory analysis is generally divided into the phases of collection of primary data specific to the foreground processes of the product system, modelling of the product system and definition of the calculation procedures necessary for the accounting of the input flows (materials, energy, resources) and output flows (products, waste to treatment, emissions) along the entire life cycle, and in the selection of datasets for the modelling of secondary processes (background processes).

An in-depth analysis based on evaluating the availability of data for LCA studies highlights that the data for modelling the foreground processes, i.e., those processes of a product system that are

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specific to it, are generally gathered from various sources: primary industry data, expert judgement from the industrial consortium, technical reports, real-time operational data from ship owner, etc., while for modelling the background processes, i.e., the upstream and downstream supply chains associated with the energy and material resources of the foreground processes, Ecoinvent [30], GaBi [31] and GREET[1] Databases are the most used (Table 5).

TABLE 5 – LIFE CYCLE INVENTORY DATA OF THE DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW

Reference	Life cycle inventory data
Chin-Ling, J., Roskilly, A.P. [10]	Foreground processes: input and output data associated with relevant stages and processes were gathered from various sources and standardized to build up an inventory for life cycle data. In detail, manufacturing phase: modelled according to expert judgement from the industrial consortium, technical reports, textbooks, and proceedings in addition to manuals and reviews. Operational phase: the real-time operational data of a RoRo cargo ship were provided by the ship owner. The size and the operational profile of the hybrid system were determined through a model based on the power demand of the hybrid system, details of the ship, real-time data and the technical outcome of prior analysis. End-of-life phase: data were mainly derived from literature and supplemented by data in Ecoinvent database. Background process: Ecoinvent database
Maritime Battery Forum [11]	Foreground processes: data from manufactures, companies, literature, estimations. Background processes: Ecoinvent database.
Espen Nordtveit [12]	Foreground processes: data from manufactures, companies, and previous research papers. Background processes: Ecoinvent 3.3 database
Jeong, B., et al. [13]	Foreground data: variety of resources such as shipyards, product manufactures, literature, etc. Background processes: Gabi database
Jeong, B., et al. [14]	Foreground processes: the inventory is partly based on primary industry data, partly on secondary literature data. Background processes: GaBi database
Perčić, M., et al. [15]	Foreground processes: Croatian Register of Shipping, calculated data based on assumption, literature data. Background processes: GREET 2019 database.
Perčić, M., et al. [16]	Foreground processes: calculated data, literature data. Background processes: GREET 2019 database.
Wang H., et al. [17]	Foreground processes: gathered from shipowner, ship operator, literature. Background processes: GaBi database
Fan et al. [18]	Foreground processes: ship's navigator report, assumption. Background processes: GREET 2018 database.
Perčić, M., et al. [19]	Foreground processes: shipowners, literature data. Background processes: GREET 2020 database
Perčić, M., et al. [20]	Foreground processes: shipowners, literature data. Background processes: GREET 2020 database
Park, C., et al. [21]	Foreground processes: collected data, modelling, and simulation. Background processes: GaBi database
Kim, S., et al. [22]	Foreground processes: measured primary data regarding operating profiles, speed, engine output, and fuel oil consumption. Background processes: not specified
Kanchiralla, et al. [23]	Foreground processes: the input and output material flow, energy flow, and emissions are collected from different sources, including scientific articles, reports, catalogues, lab experiments, and results from pilot projects. In addition, 10 sets of interviews were conducted with various experts from relevant fields for their opinion using a structured set of questions. Background processes: Ecoinvent v3.7.1. database.
Jeong, B., et al. [24]	Foreground processes: ship operators, scenarios development and modelling. Background processes: Gabi database
Park, C., et al. [25]	Foreground processes: collected data, modelling, and simulation. Background processes: GaBi database

[1] https://greet.es.anl.gov/list.php

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Guven, D., Kayalica, M.O. [26]	Foreground processes: data from manufacture, literature data. Background processes: GREET 2021 database
Kamiya, S., et al. [27]	Foreground processes: literature data. Background process: not defined.
Hartikainen,T., et al. [9]	Foreground process: production statistics and literature data. Background processes: not defined (Not LCA study)
Conte, M., et al. [6]	Foreground process: primary and literature data. Background processes: not defined (Not LCA study)
Manouchehrinia, B., et al. [7]	Foreground process: primary and literature data. Background processes: not defined (Not LCA study)
Jiang, Z., et al. [28]	Foreground processes: primary and literature data. Background processes: database of the SimaPro software (not specified) and literature data (Tree primary life cycle stages are comprised for the BAelectrode technology, including on-sea collection of EP feed stock, EP feedstock transportation from sea-side to EP-BA. Production plant, and EP-BA production. For GOA production data from database and literature was used.)
Citalingam, K. and Go, Y. L. [8]	Foreground process: not defined. Background processes: not defined (Not LCA study)

4.4 Life Cycle Impact Assessment-LCIA

The impacts evaluation phase or Life Cycle Impact Assessment—LCIA, allows the assessment of potential impacts treating data collected in the LCI. At this point, inventory data is linked to specific impact categories and indicators, to better evaluate these impacts. The LCIA phase gives important information for life cycle results interpretation.

In the present study, the most used impact category is Global Warming Potential (eighteen studies out of twenty-three), thus Table 6 resumes LCIA results linked to this indicator. As different studies depend on different hypotheses (different databases for background data, different Life Cycle Impact Assessment Methods, different functional units…) it is not easily to compare results with each other. Nonetheless, some general conclusions can be done. The study [11] shows that the battery systems in a maritime field represent significant emissions savings and that battery cells (production process energy requirements) and battery packaging are the principal contributors to the GWP indicator. Also [12] in scenarios 2,3 and 4 declare that battery production phase is one of the principal contributor to the GWP indicator. In different studies, operation phase is also indicated as the principal contributors to the GWP indicator. From the assessed documents is possible to find that running batteries in different countries can significantly increase the environmental impact, therefore it is important to consider how the electricity used as fuel in an electric propulsion system is produced from a lifecycle perspective. The electric propulsion system using electricity produced in some countries cause more emissions than the diesel system using fossil fuels [22].

TABLE 6 – LIFE CYCLE IMPACT ASSESSMENT ANALYSIS (GLOBAL WARMING POTENTIAL) OF THE DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW (FIGURES WERE TAKEN FROM THE RESPECTIVE PAPERS)

REF	Life Cycle Assessment Analysis – Global Warming Potential
Chin-Ling, J., Roskilly, A.P. [10]	GWP (CML2001): $5.61E^{+08}$ kg CO_2 eq GWP (ILCD: IPCC): $5.61E^{+08}$, kg CO2 eq Principal contributors/processes to the indicator: > 99.0% diesel gensets
Maritime Battery Forum [11]	Case 1: Platform Supply Vessel (PSV)

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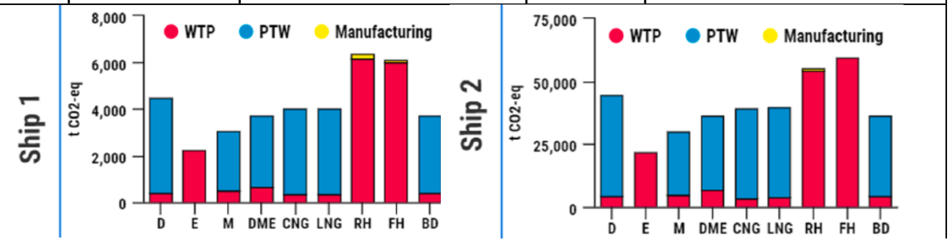
	GWP: 119 tonnes CO_2-eq Principal contributors/processes to the indicator: Battery cells (process energy requirements) and packaging. Case 2: Ferry full electric GWP: 29 tonnes CO_2-eq Principal contributors/processes to the indicator: Battery cells (process energy requirements) and packaging.
Espen Nordtveit [12]	Scenario 1: Conventional diesel combustion ferry GWP: 2.44E^{-01} kg CO_2 eq/PKT Principal contributors/processes to the indicator: operation phase of the Urban Water Shuttle (UWS) Scenario 2: UWS powered directly from the Norwegian grid GWP: 3.69E^{-02} kg CO_2 eq/PKT Principal contributors/processes to the indicator: battery production and operation have equal impact (≈30-40%), followed by the boat production (≈20%). Scenario 3: UWS with roof mounted PVs and PVs mounted on each port GWP: 4.25E^{-02} kg CO_2 eq/PKT Principal contributors/processes to the indicator: dominated by the operation and battery production phases. Scenario 4: UWS powered from the grid and additional batteries located at each port for supporting the grid during charging GWP: 5.55E^{-02} kg CO_2 eq/PKT Principal contributors/processes to the indicator: 58% battery production, 27% operation and 13% boat production.
Jeong, B., et al. [13]	Base scenario GWP (CML 2016): 3.58E^{+08} kg CO_2 eq GWP (ReCipe): 3.11E^{+08} kg CO_2 eq GWP (LCIA CML 2010): 3.58E^{+08} kg CO_2 eq GWP(TRACI): 3.58E^{+08} kg CO_2 eq Principal contributors/processes to the indicator: Operation phase for all methods Alternative scenario GWP (CML 2016): 3.12E^{+08} kg CO_2 eq GWP (ReCipe): 3.13E^{+08} kg CO_2 eq GWP (LCIA CML 2010): 3.18E^{+08} kg CO_2 eq GWP(TRACI): 3.13E^{+08} kg CO_2 eq Principal contributors/processes to the indicator: Operation phase for all methods
Jeong, B., et al.[14]	Diesel GWP: 1.6E10^{+07} kg CO_2 eq Principal contributors/processes to the indicator: use phase Battery GWP: 1.0E10^{+07} kg CO_2 eq Principal contributors/processes to the indicator: production phase
Perčić, M., et al. [15]	

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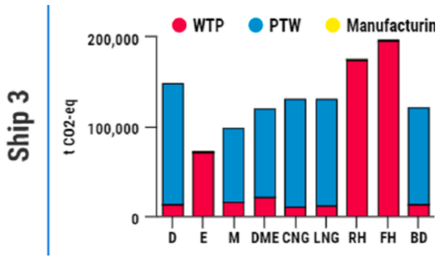
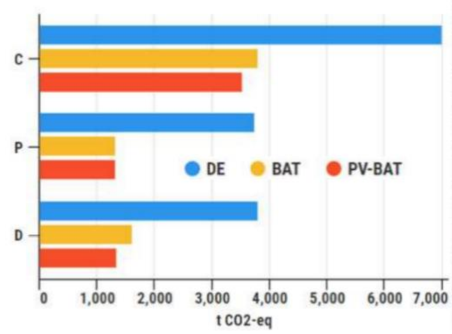
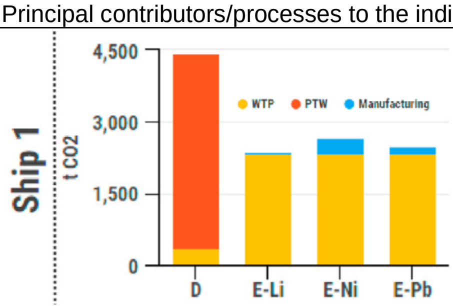
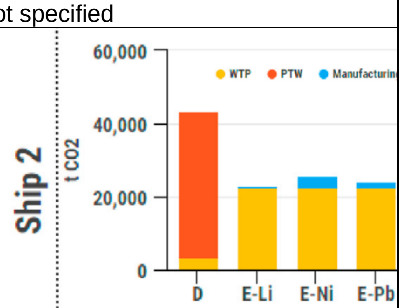
	 D diesel-powered ship E electricity-powered ship M methanol-powered ship DME DME-powered ship CNG CNG-powered ship LNG LNG-powered ship RH renewable hydrogen FH fossil hydrogen BD biodiesel WTP Well-to-Pump phase PTW Pump-to-Wake phase GWP and the principal contributors/processes to the indicator can be seen in the figures.
Perčić, M., et al. [16]	Diesel engine-powered ship GWP: 79.74 kg CO_2-eq/nm Principal contributors/processes to the indicator: Not specified Battery-powered ship GWP: 27.92 kg CO_2-eq/nm Principal contributors/processes to the indicator: Not specified PV cells-battery-powered ship GWP: 31.98 kg CO_2-eq/nm Principal contributors/processes to the indicator: Not specified
Wang H., et al. [17]	Ferry with conventional system GWP: $2.88E^{+07}$ kgCO_2eq Principal contributors/processes to the indicator: Not specified Ferry with battery system GWP: $2.03E^{+07}$ kgCO_2eq Principal contributors/processes to the indicator: Not specified
Fan et al. [18]	Not specified
Perčić, M., et al. [19]	 C cargo ship P passenger ship D dredger DE diesel engine-powered ship BAT battery powered ship PV-BAT PV-cell battery-powered ship Principal contributors/processes to the indicator: Not specified
Perčić, M., et al. [20]	

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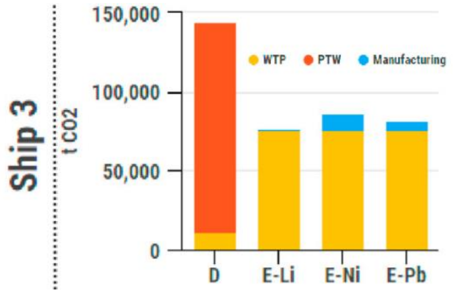
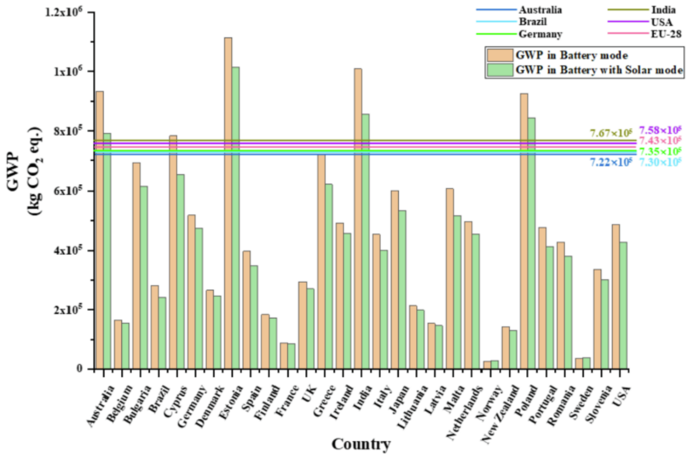
	 D diesel-powered ship E-Li electrification of a ship with a Li-ion battery E-Ni electrification of a ship with Ni-MH battery E-Pb electrification of a ship with Pb-acid battery WTP Well-to-Pump phase PTW Pump-to-Wake phase GWP and the principal contributors/processes to the indicator can be seen in the figures.
Park, C., et al. [21]	 Case 1: Diesel-electric mode Case 2: Full battery mode Case 3: Full battery with solar PV mode GWP: indicator results showed a significantly different trend depending on the energy production method of each country. Principal contributors/processes to the indicator: Not specified
Kim, S., et al. [22]	4.99 tons ship GWP (Diesel engine): 5.17E^{+06} kgCO$_2$eq GWP (Diesel engine + Battery): 4.99E^{+06} kgCO$_2$eq GWP (Diesel engine + Battery with ECMS control system): 5.03E^{+06} kgCO$_2$eq Principal contributors/processes to the indicator: Not specified 9.77 tons ship GWP (Diesel engine): 8.16E^{+07} kgCO$_2$eq GWP (Diesel engine + Battery): 5.62E^{+07} kgCO$_2$eq GWP (Diesel engine + Battery with ECMS control system): 5.73E^{+07} kgCO$_2$eq Principal contributors/processes to the indicator: Not specified 47 tons ship GWP (Diesel engine): 3.74E^{+08} kgCO$_2$eq GWP (Diesel engine + Battery): 3.73E^{+08} kgCO$_2$eq GWP (Diesel engine + Battery with ECMS control system): 3.08E^{+08} kgCO$_2$eq Principal contributors/processes to the indicator: Not specified NOTE: Authors indicate that simply increasing electricity consumption by lowering the diesel engine utilization rate and increasing the electric propulsion system utilization rate to reduce the use of fossil fuels is not an eco-friendly method. It is important to consider

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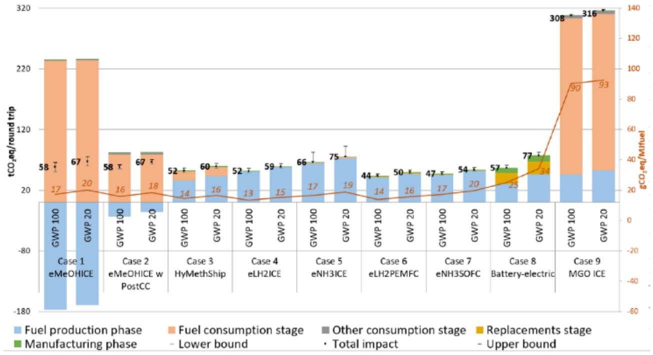
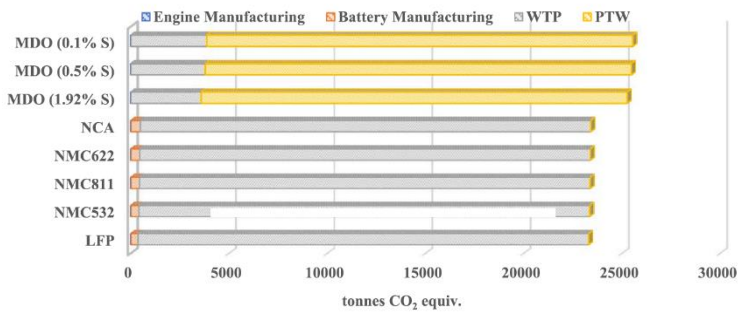
	how the electricity used as fuel in an electric propulsion system is produced from a lifecycle perspective. The electric propulsion system using electricity produced in some countries cause more emissions than the diesel system using fossil fuels.
Kanchiralla, et al. [23]	 GWP and the principal contributors/processes to the indicator can be seen in the figure. (Cases 1 and 2, the negative impact of fuel production is because the CO_2 for eMeOH synthesis is captured from air and for case 2 because not all CO_2 is captured. For case 3, the majority of CO_2 for eMeOH synthesis comes from recirculation.)
Jeong, B., et al. [24]	Hybrid ship GWP (UK diesel): 1.12E^{+07} kgCO$_2$eq GWP (World (mean) diesel): 1.45E^{+07} kgCO$_2$eq GWP (UK electricity): 3.91E^{+06} kgCO$_2$eq Principal contributors/processes to the indicator: Not specified Diesel ship GWP (UK diesel): 3.91^{+06} kgCO$_2$eq GWP (World (mean) diesel): 7.42E^{+07} kgCO$_2$eq GWP (UK electricity): 6.95E^{+07} kgCO$_2$eq Principal contributors/processes to the indicator: Not specified NOTE: Authors indicate that battery-powered ships operating in countries with high reliance on fossil-based energy resources contribute to much greater environmental impacts than the same ships dispatched to countries with a high level of renewable energy sources. Cleaner shipping is not only a matter of battery ship development but also the transition of the national electricity grid.
Park, C., et al. [25]	Authors present a large amount of data that was collected and organized based on different scenarios. The GWP value for each fuel that can be used for electric propulsion ships was presented as a functional unit. NOTE: Authors indicate that results were extremely different depending on the fuel/energy production method and the energy sources used in the production.
Guven, D., Kayalica, M.O. [26]	 WTP Well-to-Pump PTW Pump-to-Wake

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	MDO marine diesel oil GWP and the principal contributors/processes to the indicator can be seen in the figure.
Kamiya, S., et al. [27]	Not specified
Hartikainen,T., et al. [9]	Not specified (Not LCA study)
Conte, M., et al. [6]	Not specified (Not LCA study)
Manouchehrinia, B., et al. [7]	Not specified (Not LCA study)
Jiang, Z., et al. [28]	GWP (BA-electrode (Baseline)): $6.72E^{-03} \pm 3.77E^{-04}$ kg CO_2eq GWP (BA-electrode (Low)): $9.20E^{-03} \pm 4.84E^{-04}$ kg CO_2eq GWP (BA-electrode (High)): $6.25E^{-03} \pm 3.50E^{-04}$ kg CO_2eq GWP (GOA-electrode): $1.96E^{-02} \pm 1.07E^{-03}$kg CO_2eq Principal contributors/processes to the indicator: the stages of EP-drying and EP-BA production were identified as the hotspots for life cycle GWP for the BA-electrode.
Citalingam, K. and Go, Y. L. [8]	Not specified (Not LCA study)

4.5 Sensitivity and Uncertainty Analysis

Due to lack of primary and reliable data from industry, several assumptions must be made in LCA studies. Sensitivity analysis can be very important, especially in LCA studies on BESS, SuperCaps and SMES energy storage systems in marine application, where some data and information are difficult to access due to confidentiality in industry. Furthermore, sensitivity analysis is requested by the ISO 14040 standard when comparative LCAs are performed. In the present study, sensitivity analysis and/or uncertainty analysis were performed in eleven studies out of twenty-three. Uncertainty analysis using Monte Carlo simulations were performed in two studies (Table 6). Some authors investigate the impact of energy sources, in detail, the study of Jeong, B., et al. [14] explored the sensitivity of six electricity generation scenarios on emission level and Wang H., et al. [13] determine the impact of the electricity mix, applying different energy sources for electricity generation. Perčić, M., et al. [11] varied ship lifetime, i.e., lifetimes of 5, 10, 15 and 20 years were considered. Jeong, B., et al. [9] investigated how different life cycle impact models influence LCA results.

TABLE 7 – SENSITIVITY AND UNCERTAINTY ANALYSIS OF THE DOCUMENTS ANALYSED WITHIN THE BIBLIOGRAPHIC REVIEW

REF	Sensitivity and Uncertainty Analysis
Chin-Ling, J., Roskilly, A.P. [10]	Yes, sensitivity and uncertainty of the results were investigated using scenario analysis.
Maritime Battery Forum [11]	Not performed
Espen Nordtveit [12]	Yes, sensitivity analysis on the most important parameters on the GWP.
Jeong, B., et al. [13]	Yes, Sensitivity analysis was performed: (1) to investigate the influence of different life cycle impact models on the LCA results. In detail, ReCipe, TRACI and CML 2010 models were compared to the CML 2016 model. (2) to compare two different scenarios in charging and using batteries in order to determine the optimal operational practice. Case 1: Charging batteries with onboard diesel engines overnight; Case 2: Charging batteries through shore supply and extension of battery usage to supplement the transient operation. Case 1 illustrates one credible operation scenario in which the battery would be charged by the onboard diesel engine, rather than by the onshore electricity suppling facility. The charged battery would be, then, used for berthing and manoeuvring only. Meanwhile, Case 2 presents the maximum use of batteries where the batteries would be fully charged by the onshore facility and used for berthing,

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	manoeuvring and the residual battery power (equivalent to cover 1-h transient operation a day) would be also used transient phase. The result indicated that the minimum environmental impact, could be achieved with the maximum use of the batteries, as showing a clear implication of the positive relationship between the usage of hybrid and reduction in emissions. (3) To investigate the influence of using various energy sources to generate electricity: nuclear, hydroelectric, HFO, biomass, natural gas and hard coal source were compared.
Jeong, B., et al.[14]	Yes, a sensitivity analysis was performed. Six electricity generation scenarios were established to investigate the sensitivity of energy sources on emission level.
Perčić, M., et al. [15]	Yes, sensitivity analysis was performed in which the ship lifetime is varied, i.e., lifetimes of 5, 10, 15 and 20 years are considered.
Perčić, M., et al. [16]	Not performed
Wang H., et al. [17]	Yes, a sensitivity analysis is carried out to determine the impact of the electricity mix (different energy sources for electricity generation) and size comparative assessment (impact of replacing diesel engines with batteries from the perspective of weight and size).
Fan et al. [18]	Yes, uncertainty analysis method is adopted to assess the reliability of the life cycle assessment and life cycle cost assessment results.
Perčić, M., et al. [19]	Not performed
Perčić, M., et al. [20]	Yes, sensitivity analysis is performed. Diesel, electricity, and battery prices are varied by ± 20%, with an increment of 10%.
Park, C., et al. [21]	Not performed
Kim, S., et al. [22]	Not performed
Kanchiralla, et al. [23]	Yes, sensitivity analysis (assuming an anticipated carbon tax on fossil-based CO2 emissions) and energy for liquefaction is considered from 6 kWh/kg to 7 kWh/kg). Uncertainty analysis using Monte Carlo simulations is performed.
Jeong, B., et al. [24]	Not performed
Park, C., et al. [25]	Not performed
Guven, D., Kayalica, M.O. [26]	Not performed
Kamiya, S., et al. [27]	Not performed
Hartikainen,T., et al. [9]	Not performed (Not LCA study)
Conte, M., et al. [6]	Not performed (Not LCA study)
Manouchehrinia, B., et al. [7]	Not performed (Not LCA study)
Jiang, Z., et al. [28]	Monte Carlo simulations were performed in the SimaPro software.
Citalingam, K. and Go, Y. L. [8]	Yes, a sensitivity analysis is carried out by assessing the influence of initial state of charge of the battery on techno-economic parameters, not environmental. (Not LCA study)

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5 Analysis of the available technical LCA guidance on the industrial sector

The main guidance available to perform an LCA of an energy storage system is given in EN 50693:2019 [32], which defines product category rules (PCR) for life cycle assessments of electronic and electrical products and systems (EEPS). Guidelines for performing LCAs for environmental declarations are described in this document, as well as requirements on how to compile an associated LCA report, and how to develop product specific rules. The PCR is based on various documents and standards. The document also provides an extensive description of terms and definitions necessary to perform a life cycle assessment. The product category rules stated in EN 50693:2019 provide guidelines for the main stages of an LCA, from describing the functional unit and the system boundary to building the life cycle inventory, as well as how to properly allocate emissions and the appropriate units and data to be used. The document also describes the parameters to be used to model various scenarios, including transportation scenarios, use scenarios, and end-of-life (EoL) scenarios, and states the guidelines to follow when creating the LCA report. Finally, the requirements for the development of proper product specific rules (PSR) are explained. PSR are needed for specific case studies and scenarios, and must be developed by dedicated Technical Committees, since they need to reflect expert knowledge dedicated to the case in study. PSR shall be consistent with the PCR and shall not overlap.

Regarding batteries used in Electric vehicles (EV), additional guidance is provided by the Harmonized rules for the calculation of Carbon Footprint of Electric Vehicles Batteries (CFB-EV) [33], and by Battery Carbon Footprint Passport of the Global Battery Alliance [34]. This document provides further LCA guidelines, focusing on the distribution rules and the EoL and disposal of the battery, while the former describes general instructions on how to perform an LCA of a battery in all its steps, also dedicating a section to the modeling of electricity that shall be used.

PEFCR for Uninterruptible Power Systems was also taken into consideration (UPS) [35].

5.1 Product category rules

5.1.1 Functional unit and reference flow

EN 50693:2019 defines the functional unit (FU) as the quantification of the product or systems(s)' main function and provides guidelines for its appropriate determination: the FU shall be defined by the main function(s) delivered to the user, the magnitude and level of performance to be achieved for the main function(s), and the reference service life (RSL) for the reference product [32]. An adequate FU allows the comparison between different products or solutions that provide the main functions with the required level of performance. The flows needed to fulfil the FU are described by the reference flow. The reference flow shall include the quantitative number of product(s) used to fulfil the functional unit, and in addition it shall include intermediate flows, e.g., auxiliary material and packaging, including waste and discarded materials generated at each life cycle stage. These guidelines should be valid for all EEPS. Other more specific guidelines are provided in [34] and [36] for what concerns batteries for electric vehicles and other mobile applications, while [35] describes guidelines for studying Uninterruptible Power Supply (UPS) systems.

For energy-providing batteries, such as those in electric vehicles, the functional unit is defined as "one kWh of the total energy provided over the service life by the battery system, measured in kWh". The total energy equivalent to the quantity of functional unit is the total amount of electricity provided by the battery over its service time. The total energy is defined differently depending on the type of vehicle on which the battery is used.

- For light duty plug-in electric vehicle batteries, the total energy is calculated by multiplying the service life (in km) with the worst-case certified energy consumption of the corresponding vehicle family;
- for all other EV batteries, the total energy (in kWh) shall be calculated by multiplying the service life in cycles with the average amount of delivered energy over each cycle.

The reference flow is then defined as the amount of product needed to fulfil the defined function. It shall be measured in kg of battery per functional unit and is calculated as the total mass of battery divided by the quantity of functional unit [33] [34].

For UPS the functional unit is defined as "to ensure the supply of power without interruption to equipment with load of 100 watts for a period of 1 year, including backup time capacity of 5 minutes during power shortages". The corresponding reference unit shall be measured in kg of UPS per 100W over 1 year of its service life (kg UPS/100W/y) [35].

5.1.2 System boundary

In LCA product systems are models that describe the key elements of the physical systems. EN 50693:2019 states the main stages that shall be covered in an LCA [32]:

- Manufacturing stage, including relevant upstream processes and main manufacturing processing steps;
- Distribution stage;
- Use stage, including maintenance steps;
- End-of-life stage, including the necessary steps until and for the final disposal or recovery of the product system;
- Installation stage;
- De-installation stage.

The LCA shall consider all relevant flows to and from the system, so both energy and material resources and emissions to air, soil, water, and waste, all allocated to the respective life cycle stage. These system boundaries are common to all the analysed documents. Each stage shall include also all aspects related to its inputs and outputs. On the other hand, capital goods (e.g., buildings, machinery, tools, infrastructure), packaging for internal transport, and administrative overhead activities may be excluded from the system boundary.

5.1.3 Life cycle inventory

5.1.3.1 Manufacturing

The model of the manufacturing stage shall include all inputs and outputs related to the main aspects of the manufacturing, such as:

a. All the flows involved in the production of the materials and components forming the reference product, including packaging and technical documentation supplied with the product. This shall include:
    - Production of raw material necessary to produce the components, including waste flows and discarded materials generated during the manufacturing process, up to their end-of-waste status or disposal of final residues;
    - Industrial transforming and manufacturing of all the parts and components involved;
    - Transportation of materials, components, and subassemblies from the production site to the assembly site or packaging site, if present.
b. If relevant, production (extraction, treatment, transformation, transportation, etc.) of ancillary materials used in manufacturing but not supplied with the final product;

c. Assembling of the reference product and packaging components;
d. Transportation of the packaged product from packaging site to the manufacturer's last logistic platform [32]

These steps are common for all EEPS and UPS [35], guidance [33] describes additional guidelines for the modelling of the manufacturing of batteries for electric vehicles. Battery cells are usually grouped together to form battery modules, which are afterwards mounted together to form a battery pack. For these batteries the manufacturing stage shall include the production of the electrodes, the manufacture of cell components (e.g. anode, cathode, ink preparation, coating, calendaring, and slitting), assembly of the cells and assembly of the battery with the cells and the electric/electronic components. These processes shall also include the energy demand for the manufacturing of the cell and other auxiliary inputs and emissions. Manufacturing waste shall be considered, and its treatment shall be modelled in this stage. Auxiliary inputs to the manufacturing plant that are not directly related to the production of the battery may be excluded from the system boundaries [33].

5.1.3.2 Distribution

Guidance EN 50693:2019 states that the inputs and outputs that describe the distribution process associated with these aspects shall be included in this stage:

a. Transportation of the product in its packaging from the manufacturer's last logistics platform to the distributor and from the distributor to the place of installation and/or operation.
b. Processes, including the required materials and components
c. In case of repacking, end-of-life management of generated waste (e.g. material recovery, energy recovery, disposal) [32].

Battery Carbon Footprint rules from [34] describe more in depth the general guidelines that should be followed when modelling the distribution stage of batteries for mobile uses. Primary data from the producers shall be prioritised in the model, using three different approaches:

- Own truck fleet requires the fuel consumption of the truck fleet owned by the producing company. The fuel consumption is multiplied with the carbon footprint for the supply of the fuel and with the emission factors.
- Transport of goods used by the company: this approach is based on driven mileage of a known and defined means of transport that is entirely used to transport specific goods. Emission factors for this approach shall be taken from the PEF database if available and otherwise from different accessible sources. These shall be multiplied with the distance to obtain the GHG emissions for the mass of goods transported by the defined means of transport.
- Based on starting point and destination: the third approach applies if only the start and destination are known, but no further information is available. In this case, the distances shall be estimated based on a simplified logistic chain. Distances for the different transport sections may be calculated based on web calculators. Finally, a multiplication of distance and mass results in a mass-distance unit, such as tonne-kilometre (tkm) which shall be taken from the PEF database if available and otherwise from different accessible sources.

If specific data are not available, the document provides indications on how to build default scenarios to describe the distribution phase.

Regarding UPS rules, the UPS PEFCR [35] states guidelines similar to the general rules set in EN 50693:2019 for EEPS.

5.1.3.3 Installation

This stage shall be considered separately only when a specific installation process is defined for the respective product or corresponding regulatory requirements exist. The inputs and outputs that shall be included in modelling the installation stage are:

- Process, materials, and components needed for the installation
- Management of the waste generated at the installation place
- Packaging
- Discarded installation materials
- Waste associated with the installation processes [32]

PEFCR for UPS also states that the transport of a technician to the installation site shall be included [35].

5.1.3.4 Use stage

EN 50693:2019 states that the inputs and outputs associated with the following aspects shall be included in this phase:

- Energy consumption and other flows of the product during its use over the reference service life (RSL);
- Production, distribution, installation, and end-of-life of elements required to operate, service and maintain the reference product over the RSL.

Processes needed to extend the product lifetime such as repair, reuse, remanufacture shall also be taken into account in the use stage [32].

Regarding batteries for mobile applications, the energy consumed by the device during its use stage is defined by the energy losses due to the battery and charger efficiency [36], so the energy consumption associated with the use of the charger and the battery shall be considered in the model (losses due to Joule effect, thermodynamic efficiency, etc.)

For UPS, the use stage shall consider the device working under normal conditions of operation (provided in the document [35]).

5.1.3.5 De-installation

As for installation, this stage shall be considered separately only when a specific process is defined for the respective product or corresponding regulatory requirements exist [32]. The inputs and outputs associated with the following aspects shall be included in the de-installation stage:

a. Processes needed for de-installation, e.g. as specified by the manufacturer and/or applicable regulations and standards
b. Management of the waste generated at the de-installation place (collection and treatment):
    - Discarded de-installation materials;
    - Waste associated with the de-installation processes [32].

Guidance dedicated to UPS [36] include this stage in the end-of-life stage, considering also the transportation of the product from the installation site to the waste treatment facility.

5.1.3.6 End-of-life

[33] states the boundaries of the end-of-life stage, stating that it begins when the product and its packaging is discarded by the user, and ends when it is returned to nature as waste product or enters another product’s life cycle. According to EN 50693:2019, end-of-life stage modelling shall include the inputs and outputs associated with all relevant steps from de-installation to the disposal or the point of substitution:

a. Collection, transport, storage (transportation by the user to the collection point may be excluded);
b. De-pollution;
c. Fractions separation and preparation (e.g.: dismantling, crushing, shredding, sorting processes)
d. Material recovery processes (e.g.: metallurgical, chemical processes)
e. Energy recovery processes (e.g.: incineration with energy recovery, use as solid recovered fuel)
f. Disposal (e.g.: incineration without energy recovery, landfill). The disposal corresponds to the landfill or incineration of a material or a mix of materials, when it cannot be recovered as secondary materials [32].

PEFCR for batteries for mobile applications [36] states the EoL processes that shall be included for these batteries:

- Dismantling of components; the components such as casings, cooling systems, plastics and other parts are separated from the batteries.
- Conversion into recycled material: pyrometallurgical treatment, followed by hydrometallurgical treatment.
- Other operation: in case shredding processes are needed as a first (recycling) treatment, it is recommended to account for the energy consumption as well as to evaluate the possible emissions.
- Credits: as a result of cell recycling, after the refining, certain flows are credited. The mass of these flows are calculated according to the stoichiometric calculation of the cell materials input proportionally to the cell recycling outputs

Extensive guidelines on the end-of-life and recycling of batteries are provided in BCF Rules [34], describing system boundaries to be considered, the functional unit and several processes of recycling (e.g. discharge and dismantling, pyrolysis, shredding, metallurgical treatments), including guidelines for allocation when necessary. Regarding allocation, the document states that the Cut-off approach is to be preferred to the Substitution approach, when possible, since it provides the most transparency and accuracy for EoL allocation. The unrecyclable materials included in the battery shall be stated in the model, and their EoL processing shall be stated (landfill or incineration). To be considered recyclable, a material shall have dominant recycling processes available (economically beneficial), if that's not the case the material shall be classified as unrecyclable [34].

For UPS, the dedicated PEFCR [35] states that inputs and outputs associated with these processes shall be included in the EoL stage:

- Transportation to collect the decommissioned product and transport from installation site to the waste treatment facilities;
- Treatment processes, including depollution treatment of items to be sent to special EoL product treatment centres, up to final treatment.

5.1.3.7 Cut-off rules

EN 50693:2019 states the general rules to be applied as cut-off criteria. Exclusion of inputs and outputs due to cut-off is needed for an efficient calculation procedure and shall not be applied to hide data. Following the general LCA practice, the cut-off criteria are set to a maximum of 5% of the overall environmental impact of the analysed product system given by its life cycle impact assessment results. Additional criteria for specific product systems may be developed and defined in dedicated PSR [32].

According to PEFCR for UPS [35], the following processes shall be excluded based on the cut-off rule:

a. Manufacturing stage:
   - Capital goods
   - Energy consumptions for the use and maintenance of the assembly site
b. Distribution stage:
- Energy use and capital goods for the storage at the Distribution Centre (DC)
c. Installation stage:
   - Installation processes
   - Collection and treatment of installation wastes (product packaging)
d. Use and maintenance stage:
   - Waste treatment of decommissioned fans, capacitors, and PSUs
   - Waste treatment of glass from decommissioned lead-acid batteries
   - Production, transport, and end of life of replacing component packaging

In addition, Waste treatment of display panel (LCD) shall be excluded from the system boundary, ensuring is no artificial credits due to the recycling of the LCD, since its production shall not be accounted for at the manufacturing stage [35].

5.1.4 Allocation rules

In case allocation cannot be avoided to solve multifunctionality, allocation shall be based on attributional principle. Physical properties, such as mass, net calorific values, etc., shall be preferred, otherwise economic aspects, such as man-hours, operating hours or manufacturing cost may be used [32]. If economic allocation is applied, minimum 12 months global price averages shall be used [33].

Guidance [33] describes guidelines for economic allocation in processes with base and precious metals as outputs. Economic allocation shall be applied where platinum group metals or other precious metals are separated from base metals. Economic allocation shall be applied only at the processes of extraction, using 10-year average global market prices, to avoid the impact of high volatility of metals in the global market. The used market prices shall reflect the specific conditions in terms of e.g., purity or other properties which have an impact on the global market price. Additional allocation rules regarding energy and auxiliary inputs of production lines, as well as allocation of the battery casing/housing in EV batteries, are provided in the document [33].

PEFCR for UPS [35] recommend to not apply allocation, advising to use allocations set up in databases and to not modify them. If allocation is unavoidable, subdivision shall be used for processes that can be directly attributed to certain outputs (e.g. energy use and emissions related to manufacturing processes). The norm describes how to allocate upstream burdens in case the processes cannot be subdivided:

a. Material production shall be allocated to process outputs using a mass allocation method.
b. Electronic components shall be allocated to process outputs per unit produced.
c. Printed wiring board shall be allocated to process outputs using a surface allocation method.

The PEFCR does not provide default allocation values for UPS [35].

5.1.5 Units

For what concern units, units from the SI should be used in the LCA and LCA report, although in some cases non-SI units may be used, for example kW (MW) for power and kWh (MWh) for energy [32].

5.1.6 Electricity modelling

For the relevance to the present project, a detailed account on how to treat electricity seems necessary. Indeed, guidance [33] and [36] supply rigorous guidelines to model the production of the electricity used in the LCA. These guidelines shall only be used when company-specific information is collected. If the electricity is purchased, the electricity mixes to be used are described in hierarchical order:

a. Supplier-specific electricity product shall be used if available, and the set of minimum criteria to ensure that the contractual instruments are reliable is met.
b. The supplier-specific total electricity mix shall be used if available, and the set of minimum criteria to ensure that the contractual instruments are reliable is met.
c. As a last option the “country-specific residual grid mix, consumption mix” shall be used. Country-specific means the country in which the considered stage occurs. Using the residual grid mix prevents double counting with the use of supplier-specific electricity mixes in a) and b).
d. If all the above criteria are not met, then use use the country- or grid specific average consumption mix.

If there is a 100% tracking system in place for a country, option a) shall be used, and for the use stage the consumption grid mix shall be used. To ensure the reliability, accuracy and consistency of the data and information from suppliers, a set of minimal criteria needs to be met. A contractual instrument used for electricity modelling shall:

a. Convey attributes:
    - Convey the energy type mix associated with the unit of electricity produced.
    - The energy type mix shall be calculated based on delivered electricity, incorporating certificates sourced and retired on behalf of its customers. Electricity from facilities for which the attributes have been sold off (via contracts or certificates) shall be characterized as having the environmental attributes of the country residual consumption mix where the facility is located.
b. Be a unique claim:
    - Be the only instruments that carry the environmental attribute claim associated with that quantity of electricity generated.
    - Be tracked and redeemed, retired, or cancelled by or on behalf of the
c. Be as close as possible to the period to which the contractual instrument is applied

If the electricity is not purchased, but the on-site generated electricity is used, then it is important to distinguish between two situations:

a. No contractual instruments have been sold to a third party.
b. Contractual instruments have been sold to a third party

In the former case, the producer model its own electricity mix for the amount of on-site generated electricity, while in the second case it is mandatory to use ‘country-specific residual consumption (grid) mix’.

If the total amount of electricity produced on-site exceeds the amount consumed on-site within the defined system boundary and is sold, this system may be seen as a multi-functional process providing two functions (e.g., product + electricity) and as such must be modelled following the ISO hierarchy approach.

In [35] there is no such a detailed analysis of electricity, but it is suggested to use the 'country-specific residual grid mix, consumption mix'.

Global Battery Alliance (GBA) in its general rulebook [37] is more flexible and gives two sets of calculation rules: one based on the Harmonized Market Approach (HMA) and the other on Physically Modelled Approach (PMA).

5.2 LCIA

The European standard [32] suggests a list of recommended impact categories and characterization factors, provided in Annex B and based upon the recommendations of the ILCD handbook [3]. In any case, the source for the recommended impact categories is the European Commission and PEFCR regulation [38]. Of course, in PEFCR documents [35] [36] these are the impact categories to be used.

In [33] [34] [37] the only impact category is climate change.

6 Guidelines for conducting LCAs of the innovative combined energy storage technologies in marine applications

This section provides guidelines on how to conduct an LCA study aimed at assessing the innovative combined ESS (battery technology plus supercapacitors or SMES) in the electrical vessel and to compare them with the traditional solution based only on batteries. The guideline was drawn up based on the international standards ISO 14040 and ISO 14044 . Other methodological references were the "International Reference Life Cycle Data System" (ILCD) manual of the Joint Research Center - JRC [3] and the recommendations of the European Commission relating to the use of common methodologies to measure and communicate the environmental performance of the life cycle of products and organizations [4], [5]. Furthermore, some indications have been provided based on the analysis of the state of the art described in Section 3 and 4. The guidelines have been developed according to the sequence of methodological phases that characterize an LCA study according to the reference standards already mentioned.

6.1 Recommendations for goal and scope definition

<u>Goal definition</u>

The goal of the LCAs studies conducted within the V-ACCESS project is to assess the innovative combined ESS (battery technology plus supercapacitors or SMES) in the electrical vessel and to compare them with the traditional solution based only on batteries.

<u>The investigated system</u>

The investigated system shall be described in detail reporting all the information necessary for its correct identification. With reference to the V-ACCESS selected use cases the following information are required:

- Type of vessel and main characteristics.
- Installed combined ESS (battery plus SuperCaps or battery plus SMES).

- All the parameters needed to correctly identify the ESS to ensure a meaningful comparison between the innovative and the traditional solutions. In detail, the main technical characteristics of each ESS sub-component and the operational profile of each ESS technology shall be described in detail, e.g., for the battery: the cell chemistry, the rated power, the energy capacity, the lifetime, the efficiency, the depth of charge, and technical information on the other battery pack components shall be available; for the SuperCaps the main parameter regards: rated capacitance and voltage, specific energy, maximum peak current, power (10ms ESR / 1s ESR), operating temperature range, and lifetime. Finally, for the SMES, the rated power, cycle efficiency, lifetime, power conditioning system, the cryogenic system, overall weight and volume.

Function, functional unit and reference flow

Concerning the V-ACCESS project, for each case study selected within the WP1 the provided function shall be correctly identified to select the most appropriate FU to conduct the LCA study. For example, for electric vessels that provides the service of "transporting passengers, vehicles and cargo" an appropriate FU can be "ton-kilometre" considering the whole service life, while for electric offshore support vessels the FU can be defined as "one operating hour" to perform a specific task. To compare the different technologies investigated within the V-ACCESS project, in relation to the same function, the selected FU can be "1 kWh of the total electrical energy provided over the service life by the power system technology to perform a specific task". It is important to understand that the functional unit should always include a function and not simply be a physical quantity [29]. More specifically, the definition of the FU shall describe the qualitative aspects and quantify the quantitative aspects of the selected function which generally involves answering the questions: "What does it do?", "How much?", "How well?", "For how long?

Based on the ESS characteristics and the defined FU, the reference flow can be determined as the amount of product needed to realise the FU. For the V-ACCESS case study, the reference flow associated to a specific FU can be, for example, a certain number of batteries characterized by a specific rated capacity coupled with a SuperCap characterized by a specific capacitance.

System boundaries

The system boundaries determine which stages of the process must be included in the LCA, and this choice must be consistent with the objective of the study. The cradle-to-gate analysis considers raw material extraction and processing, as well as the ESS manufacturing itself, while excluding use- and End-of-Life- (EoL) phase. If analysis is pointed to a particular use case, as ESS in vessels in marine applications, system boundaries must be through the use phase and EoL. Whenever possible, it is recommended to go through Cradle-to-Grave analysis, considering all phases of an ESS during its life cycle.

Approach to solve the multifunctionality

To solve potential multifunctionality processes within the V-ACCESS case studies the ISO 14044 hierarchy of solutions shall be followed:

- First choice: subdivision of unit process. It consists in increasing the resolution of the modelling by dividing the multifunctional unit process into minor units to see whether it is possible in this way to separate the input and output flows associated to the main product/function from those associated to the additional (secondary) product/function.
- Second choice: system expansion. It consists of credit the multifunctional process with the

inputs and outputs which are avoided when its additional (secondary) product/function replaces an alternative way of producing it.

- Third choice: allocation. When both subdivision of unit process and system expansion are not feasible the ISO 14044 standard recommends allocation that consists of dividing the inputs and outputs of the multifunctional process or system between the different products or functions.

<u>Selection of impact assessment methods and environmental impact categories</u>
The selection of the impact categories and evaluation methods shall be carried out based on the following indications:

- Impact categories, category indicators and characterization models shall be internationally recognized.
- Impact categories, category indicators and characterization models must avoid double counting and cover a wide range of environmental impacts in order to avoid burden-shifting among impact categories.
- The characterization model of each category indicator shall be reliable from a technical and scientific point of view. It shall be based on clearly identifiable environmental mechanisms and reproducible empirical observations.
- Category indicators must be environmentally relevant.

6.2 Recommendations for Life cycle inventory analysis

During the inventory analysis it is necessary to identify, with reference to each phase of the life cycle and each process unit included in the analysis, the input flow, in terms of consumption of materials and energy resources, and the output flow, in terms of pollutant emissions into the air, water and soil, wastewater, products and any co-products.
The data collection must include both quantitative and qualitative information to obtain a modelling that is representative of the analysed product system.
The data collected can be divided into:
• primary data from industrial partners, i.e., specific process data on energy and material resources, coming from direct surveys, which are generally used for modelling the foreground processes. With reference to the V-ACCESS case studies, these data can include, ESS bill of materials, vessel's operational profile, etc.
• secondary data, i.e., average data from environmental databases, which are generally used in the modelling of background processes. Examples of the most up-to-date and complete databases include Ecoinvent Database [30] and GaBi database [31].
Furthermore, if primary and secondary data are not sufficient for product system modelling, data collection can be completed through literature studies (tertiary data).
Concerning the V-ACCESS case studies, primary data from industrial partner shall be available to create a detailed LCA model of the manufacturing process of each innovative combined ESS. Moreover, the operational profiles of the combined ESS in performing the investigated functions shall be based on primary data or obtained through energy model of the investigated systems. Concerning the end-of-life phase, it should be modelled based on scenarios developed according to the current practice and to the newly approved Batteries Regulation which was published on July 28, 2023 in the Official Journal of the European Union. The text will therefore enter into force in 20 days and will then be applicable from 18 February 2024 (6 months after entry into force) and on waste electrical and electronic equipment (Directive 2012/19/EU).

The life cycle model of the investigated case study shall be implemented within software specifically developed to conduct LCA study like as: SimaPro software, Gabi, Open LCA, etc.

6.3 Recommendations for life cycle impact assessment

According to the indication on the selection of impact assessment methods and environmental impact categories listed at Paragraph 6.1, in this guideline the Environmental Footprint (EF 3.0) method is recommended as it represent one of the most updated method covering a wide range of environmental impact categories [38]. EF methods cover 16 environmental impact categories characterized by three levels of recommendations: Level I "recommended and satisfactory", Level II: "recommended but in need of some improvements", and Level III "recommended, but to be applied with caution". In this guideline only impact categories with reliability level I and II are recommended. An exception is represented by "Resource use, Minerals and Metals" impact category that is also stated, although at level III, because of the relevance of natural resource availability in the field of energy storage and energy transition [39]. To provide a deeper insight on this paramount impact category, it is also suggested to assess the impact on resource consumption with a further indicator, the Life Cycle Commodities Costing (C-LCC) developed by RSE [40]. Such indicator, developed by RSE, is based on market prices and quantifies, in monetary units, the level to which a product utilizes natural resources during its life cycle. Within the C-LCC, costs are handled as characterization factors, while the classification and characterization phases are carried out like in a conventional Life Cycle Impact Assessment. Market prices, or their proxies, are used as a measure of resource scarcity and, for this reason, relies on fewer, more reliable, and up-to-date assumptions with respect to other method based on information that is very uncertain: the ultimate reserves of given resources present in the Earth's crust and the deaccumulation of such reserves [41]. For further information about the C-LCC indicator, please refer to Mela et al. [40].

Table 8 recap all the impact categories included within the EF 3.0 scheme, those recommend for the environmental assessment of the V-ACCESS case studies are highlighted in bold.

TABLE 8 – IMPACT CATEGORIES, ROBUSTNESS, IMPACT CATEGORIES INDICATORS AND UNITS USED BY EF 3.0 METHOD [38].

EF Impact category [Robustness]	**Impact category Indicator**	**Unit of measure**
Climate change (GWP) [I]	Global warming potential (GWP100)	$kgCO_{2eq}$
Ozone depletion [I]	Ozone depletion potential (ODP)	$kgCFC\text{-}11_{eq}$
Ionising radiation, human health [II]	Human exposure efficiency relative to U235	kg U^{235}eq
Photochemical ozone formation, human health [II]	Tropospheric ozone concentration increase	kg $NMVOC_{eq}$
Particulate matter [I]	Impact on human health	disease incidence
Human toxicity, non-cancer [III]	Comparative Toxic Unit for humans (CTUh)	CTU_h
Human toxicity, cancer [III]	Comparative Toxic Unit for humans (CTUh)	CTU_h
Acidification [II]	Accumulated Exceedance (AE)	mol H^+_{eq}
Eutrophication, freshwater [II]	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}
Eutrophication, marine [II]	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}
Eutrophication, terrestrial [II]	Accumulated Exceedance (AE)	mol N_{eq}

Ecotoxicity, freshwater [III]	Comparative Toxic Unit for ecosystems (CTUe)	CTU_e
Land Use* [III]	Soil quality index	Dimensionless pt
Water use [III]	User deprivation potential (deprivation-weighted water consumption)	m^3 water eq of deprived water
Resource use, fossils [III]	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ
Resource use, minerals, and metals [III]	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}
* Refers to occupation and transformation		

6.4 Recommendation for life cycle interpretation

In the interpretation phase, the results obtained in the previous stages of inventory analysis and impact assessment are analysed, in line with the objective and field of application, to identify the significant aspects and to draw conclusions and recommendations accordingly.

The Interpretation consists of three stages:

1. Identification of significant aspects: in this phase the results obtained in the inventory analysis and in the evaluation of the environmental impacts shall be presented with reference to the phase of the life cycle and to the process to which they refer, to facilitate the identification of the "hot-spots" and provide indications on possible actions aimed at the eco-design of the investigated technologies.
2. Completeness and consistency check: this phase has the objective of verifying that all relevant information and data necessary for interpretation are available and complete. Otherwise, it is necessary to redefine the objective and scope of the study.
3. Conclusions and recommendations: the objective of this phase is to draw conclusions and recommendations and to identify the limitations of the study.

7 Conclusions

The deliverable reported on the state of the art of LCA studies applied to the ESS technologies investigated within the V-ACCESS project. The analysis showed that only one study is available which evaluates the global warming associated with an innovative power system consisting of the combination of supercapacitors and lead-acid batteries in marine applications. However, this study does not apply the LCA methodology. Seventeen documents report on LCA applied to traditional electric vessel based on battery. These studies will provide a useful support in quantifying the potential environmental benefits associated with the innovative combined ESS (battery technology plus supercapacitors or SMES) in the electrical vessel with respect to the traditional solution based only on batteries.

Moreover, the guideline aims to guide analysts in applying the LCA aimed at assessing the innovative combined ESS (battery technology plus supercapacitors or SMES) in the electrical vessel and to compare them with the traditional solution based only on batteries. The guideline was drawn up based on different documents relating to the LCA methodology and the LCA studies of electric propelled ship based on battery powered technology. The LCA procedure has been examined in detail and the general rules and procedural steps have been specific for the case study of the innovative combined ESS, to provide methodological indications that allow a correct application of the methodology.

Finally, the very recent publication of the new “REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL” of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, requires that any battery sold on the European market has its own carbon footprint[2]. For this reason, the JRC has issued a draft on battery carbon footprint and once finalized, this will be the accompanying document of the new directive to perform the carbon footprint.

The analysis of this document as well as of the other European driven category rules has confirmed that the methodology here proposed to assess the ESS technologies is also compliant with the new European policies.

The guideline presented in this deliverable is based on international standards and on the specific literature. In the final version of D4.1, the guideline will be updated based on the results of the LCA applied to V-ACCESS case studies.

[2] "Rechargeable industrial batteries with a capacity greater than 2 kWh, LMT batteries and electric vehicle batteries placed on the Union market should therefore be accompanied by a carbon footprint declaration."

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