

D4.2 – LCA methodology and assessment for on board ESS - update

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1 Introduction

Research on environmental sustainability in maritime transport and shipping is a relatively new and growing interdisciplinary field of study [1]. Several studies have explored the potential of different technologies to contribute to emissions reductions of maritime vessels focusing mainly on the electrification of ships through the implementation of fully electric or hybrid marine power systems for propulsion. In the case of fully electric vessel, the energy storage system (ESS) must supply all the vessel load. In the case of a hybrid marine power systems, diesel/gas generators (DGs) and ESS supply the vessel loads; therefore, an energy management strategy is required to determine how to share the load between DGs and ESS. Among the storage devices, hybrid energy storage systems (HESS) that integrate supercapacitors (SC) or a Superconducting Magnetic Energy Storage (SMES) with battery technologies are explored within the V-ACCESS project. In fact, the power requirements for a specific marine application can exceed the limits of a Battery Energy Storage System (BESS) sized based on energy capacity leading to the need to oversize the BESS for fulfilling the power requirements. So, high-power ESS technologies (like SC or SMES) can be considered instead of batteries to fulfil the power requirements. At this early stage of technology implementation, Life Cycle Assessment (LCA) [2], [3] is necessary to guide research towards an optimal compromise between technical/design requirements and environmental sustainability. In this framework, Deliverable D4.1 – LCA Methodology and Assessment for On-Board ESS, submitted in Month 7 (M7), developed a comprehensive literature review on LCA studies related to batteries, SCs, and SMES in marine applications. It also analysed the available technical LCA guidelines, such as the European Commission’s Product Environmental Footprint Category Rules (PEFCR), focusing on industrial sectors relevant to the technologies proposed within the V-ACCESS project (e.g., batteries and the maritime sector). Finally, the deliverable provided a detailed guideline for conducting LCAs on the investigated HESSs implemented in marine applications.

This deliverable (D4.2) presents an updated version of Deliverable 4.1 (D4.1). Specifically, this updated version includes the LCA of the V-ACCESS case studies analysed by WP1 to assess their environmental sustainability. The evaluation is conducted by comparing them with the corresponding reference cases, which represent the current state of technology. The case studies in which the HESSs implementation are investigated are:

- Electric ferry: a fully electric roll-on/roll-off vessel with an overall length of 74 m and a breadth of 15 m. It is double ended. The electric ferry power system consists of a BESS.
- Offshore Supply Vessel – Active Heave Compensation (OSV-AHC) system: a ship specially designed to supply offshore oil and gas platforms and other offshore installations. It is characterized by an overall length of 94 m and a breadth of 21 m. The OSV is equipped with a hybrid marine power system composed of diesel generators and a BESS.
- Trawler: is a vessel mainly used for fishing with overall length of 80 m and a breadth of 17 m. The trawler is equipped with a hybrid marine power system composed of diesel generators and a BESS.

The study was conducted in compliance with international standards ISO 14040 and ISO 14044 [2], [3]. Both primary data, specific to the examined systems, and secondary data were used for the LCA. Primary data

on foreground processes were obtained from the consortium industrial partners, who provided the available information regarding both storage systems construction and vessels operational phases. Any gaps in the data were addressed by consulting specialized literature. Secondary data for modelling background processes were sourced from the Ecoinvent 3 database (version 3.9.1) [4]. The environmental impact assessment was conducted across a broad range of impact categories, with a particular focus on the “climate change” category, applying the EF 3.1 method developed by the European Commission (UE/2021/2279) [5].

The deliverable consists of five main parts. The first provides an update on the literature review on LCA studies for batteries, supercapacitors, and superconducting magnetic energy storage systems (in the following BESS, SC, and SMES, respectively) in marine applications (Chapter 3). The second part concerns the update analysis of the available technical LCA guidelines (such 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 (Chapter 4). The third part focuses on the application of the LCA methodology to the V-ACCESS case studies and the interpretation of the obtained results (Chapter 0). Chapter 6 provides eco-design strategies aimed at improving the environmental sustainability of the investigated systems. Finally, Chapter 7 summarizes the main conclusions of the study.

2 Abbreviations and acronyms

Table 1 presents the acronyms and abbreviations used throughout this report.

Table 1 – Abbreviations and acronyms

BESS	Battery energy storage system
EoL	End of Life
ESS	Energy Storage System
EV	Electric Vehicles
FU	Functional Unit
GBA	Global Battery Alliance
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
PCR	Product Category Rules
PEFCR	Product Environmental Footprint Category Rules
PSR	Product Specific Rules
SC	Supercapacitors
SMES	Superconducting Magnetic Energy Storage
V-ACCESS	Vessel Advanced Clustered and Coordinated Energy Storage Systems

3 Literature analysis update

This section presents an updated version of the literature review conducted in Deliverable D4.1. The initial analysis, which focused on identifying key studies related to the application of Life Cycle Assessment to BESS, SC and SMES) in marine applications, has been expanded. The objective of this update is to incorporate newly identified relevant papers and, where applicable, include recent findings that have emerged since the submission of the original deliverable.

The initial literature review conducted for Deliverable D4.1 involved an extensive search across databases such as ScienceDirect, Scopus, and Google Scholar using keywords related to LCA and energy storage systems in marine applications. After the screening process, which included abstract analysis and eligibility criteria—23 relevant articles were selected: 17 focused on BESS, four on SCs, and two on SMESs. For BESS, only studies specifically related to marine applications were included, excluding papers on battery technologies in non-marine contexts such as automotive applications. On the other hand, for SMESs and SCs, studies from other fields were also considered due to their potential relevance in supporting the development of LCA models for these systems in the marine applications analysed within the V-ACCESS project. This approach was necessary because the literature review identified only one study on SC and none on SMES specifically in marine applications. The literature review update was conducted using the same methodology and criteria previously defined. The updated search identified only three additional relevant studies, all focusing on hybridization approaches that combine traditional combustion engines with battery storage [6], [7], [8]. No articles on the application of SMESs or SCs in maritime contexts were identified. The three newly identified articles are described in the following section. Previously identified studies related to marine applications are listed in the Appendix, while a detailed analysis of these documents is available in Deliverable 4.1.

Perčić et al. [7] investigated the implementation of different alternative powering options onboard Croatian ferries, considering real operating loads. A simulation of their use for ship power was carried out using specialized microgrid optimization software, which enables both system optimization and Life-Cycle Cost Assessment (LCCA). In addition to optimization and economic assessment, a LCA was performed to determine the most suitable power system for a given vessel, considering its operational schedule and load while meeting both environmental and economic criteria. The study examined two ferries: “Ferry 1” operating on a 3 km route in Croatia with 28 trips per day (each lasting approximately 15 minutes), and “Ferry 2” which serves Croatia’s longest ferry route, connecting Split with Vis Island on a 140-minute journey, operating four times per day. The study assumes that these operational schedules remain unchanged over the ships' 20-year lifespan. The LCA was conducted using GREET 2022 software and assessed emissions over the 20-year operational lifetime, categorizing them into three groups: manufacturing emissions, well-to-tank (WTT) emissions, and tank-to-wake (TTW) emissions. Manufacturing emissions originate from the production process of the main power system components (e.g., generator, battery). WTT emissions account for those generated throughout the fuel cycle, including raw material extraction, fuel production, and distribution. TTW emissions correspond to those released during ship operation (i.e., exhaust emissions). The study evaluated three key impact categories: climate change, acidification, and human toxicity. The authors examined various ship power systems, including (i) a conventional diesel generator system (baseline scenario), (ii) a fully electric power system using a shore-charged BESS with either Lead-Acid Batteries (LAB) or Lithium-ion Batteries (LiBs), and (iii) a hybrid system integrating a diesel generator with a battery to enhance efficiency and reliability, where the battery is charged using excess power from the generator. Other

systems considered in the study included methanol-powered ships, fuel-cell-powered vessels using Liquefied Natural Gas (LNG), and conventional diesel-powered systems operating on a biodiesel-diesel blend (B20). LCA results indicated that the LNG fuel-cell system was the most environmentally friendly option. Hybrid propulsion systems did not provide significant emission reductions, emphasizing the importance of carefully selecting propulsion systems to balance economic and environmental objectives. Full electrification using LiBs was identified as the second-best option, reducing greenhouse gas (GHG) emissions by 46% (Ferry 1) and 40% (Ferry 2) compared to a diesel-powered ship. This solution was found to meet both environmental and economic criteria and was deemed the most suitable propulsion system for the ferry under consideration.

Laurence and Bai [6] conducted an LCA study to assess and compare the environmental and economic impacts of diesel internal combustion engine (ICE) and full electric battery power systems. The study also examined how electricity sources and battery types influence environmental performance. The two power systems were evaluated using the same case study vessel, a small containership operating between the port of Porsgrunn and the port of Brevik, covering a round-trip distance of approximately 26 km. The ship has a capacity of 120 TEU and a deadweight of 3,200 tons. In the diesel ICE scenario, the vessel is powered by a diesel engine with a maximum output of 1,768 kW, whereas in the full electric battery scenario, it operates using a marine rack system equipped with lithium-ion (Li-ion) 55 Ah NMC/G batteries with a total capacity of 6.7 MWh. Two types of NMC battery are considered in the study: NMC111 and NMC811.

The functional unit of the study is the total distance travelled by the ship over its lifetime, estimated at 23,400 km. The system boundaries were defined following a cradle-to-grave approach. For the diesel-powered ship, they include diesel engine production and transportation, diesel fuel production, engine operation, and decommissioning. For the all-electric ship, they encompass battery production and transportation, electricity generation, battery operation (including replacements), and decommissioning. The ship's operational life cycle was modelled over a 10-year period. The CML-IA method developed by Leiden University was selected for the life cycle impact assessment [9]. The study highlighted that the full electric battery power system has lower environmental impacts than the ICE system in six out of eleven impact categories: abiotic depletion potential – fossil fuels, acidification potential, eutrophication potential, global warming potential (100 years), ozone layer depletion potential, and photochemical ozone creation potential. In contrast, the ICE system performs better in the remaining five categories: abiotic depletion potential – elements, freshwater aquatic ecotoxicity potential, human toxicity potential, marine aquatic ecotoxicity potential, and terrestrial ecotoxicity potential. This is largely due to the extraction and processing of critical materials such as copper and cobalt, which are essential for battery production and contribute significantly to its environmental impact, leading to higher burdens in these categories compared to the ICE system.

Perčić et al. [8] analysed the replacement of a diesel engine on board two fishing ships (purse seiner and trawler) with a battery in a lifetime framework. The authors performed an environmental analysis with LCA to investigate the life-cycle impact on climate change, human toxicity, and acidification of different LiBs (LFP, NCA, NMC111, NMC532, NMC622, NMC811). The study deals with cradle-to-gate assessments, where the cradle refers to the resource extraction, and the gate refers to the output of a ship power system (tailpipe emissions). The functional unit selected to compare the investigated power systems is 1 kWh of the energy consumed. The system boundary is placed on the ship itself, where only emissions related to the ship's power system are investigated. This paper investigates emissions during the 20 years of the ship's lifetime, and they can be divided into three groups: Manufacturing (M), Well-to-Tank (WTT), and Tank-to-Wake (TTW)

emissions. Among the different battery types, the LiB is indicated as the most convenient one. Moreover, LiB has different chemistries, i.e., different materials that constitute the electrodes, which offer different characteristics regarding energy density, lifetime, price, safety, etc. The LCA of the existing and alternative powering options is performed using LCA software GREET 2022. The LCA comparison for each impact category indicated that each considered battery technology (battery chemistry) is environmentally friendlier than the existing powering option. It is mainly due to the high amount of TTW emissions released during the diesel combustion in an engine. Among the different batteries, the most environmentally friendly option is the LFP battery, while the second alternative with the lowest emissions is NMC111. LFP battery results in 40% lower life-cycle GHG emissions than those released by diesel-powered ship. Regarding the impact on acidification and human toxicity for both fishing vessels, the LCA results showed that the major contributor is the diesel-powered ship. NCA and NMC811 batteries result in the highest life-cycle emissions, mainly due to the high number of their replacements during the 20 years of the ships lifetime.

The newly analysed studies examine different ship propulsion options, highlighting that full electrification with lithium-ion batteries significantly reduces GHG emissions compared to conventional diesel engines. However, the environmental benefits depend on the operational context and energy sources. Hybrid systems offer limited emission reductions, emphasizing the need for careful selection of propulsion technologies. While electric systems perform better in several impact categories, such as global warming potential, acidification, and ozone layer depletion, the extraction and processing of battery materials contribute to other environmental burdens, including human toxicity, freshwater and marine ecotoxicity, and resource depletion.

Table 2 presents an overview of the selected studies within the literature review update, while the documents analysed within the bibliographic review presented in Deliverable D4.1 are recapped in Table 36 in the Appendix (Chapter 9, Paragraph 9.1).

Table 2 – Overview of selected studies, their marine applications, power systems, and key environmental results.

Reference	Marine application and ship type	Technology/Power system	Main LCA results
Perčić et al. [7]	Ferry 1 (3 km route, 15 min trip, 28 trips/day) and Ferry 2 (Split–Vis route, 140 min trip, 4 trips/day)	Hybrid system (Diesel generator + Battery) with Lead-Acid or Lithium-ion Batteries, Methanol-powered, Fuel-cell powered by LNG	LNG fuel-cell system is the most environmentally friendly option. Hybrid systems show limited emissions reduction. Full electrification with LiBs reduces GHG emissions by 40-46%.
Laurence and Bai [6]	Small containership (120 TEU, 3,200 tons) operating between Porsgrunn and Brevik (26 km round-trip)	Diesel Internal Combustion Engine (ICE), All-electric Battery Power System (Lithium-ion Batteries)	All-electric battery system has lower environmental impacts in six out of eleven categories, particularly in global warming potential and acidification. Diesel ICE system performs better in critical material categories.
Perčić et al. [8]	Fishing vessels: Purse seiner and trawler	Diesel engine replaced with Lithium-ion Batteries (LFP, NCA, NMC111, NMC532, NMC622, NMC811)	LiB-powered vessels result in 40% lower life-cycle GHG emissions compared to diesel-powered vessels. Diesel engines are the major contributor to acidification and human toxicity. NCA and NMC811 batteries show higher emissions due to frequent replacements.

The identified articles predominantly focused on battery-powered electric vessels or hybrid marine power systems combining conventional ICE generators with batteries. This highlighted the need to further explore

the environmental sustainability of integrating batteries with SMES and supercapacitors in marine applications.

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

In this chapter the updates to the main guidance documents analysed in the Deliverable 4.1 are reported. The main reference considered is the EN 50693:2019 [10], which did not receive an updated version at the time of this publication. The PEFCR for Uninterruptible Power Systems which was considered in the previous deliverable was not updated either [11]. Considering the three other documents considered [12], [13], [14], they all received minor or major updates since the publication of the previous document. Only the new directives that may concern this work will be reported in this document, the detailed analysis of rules and documentation is available in Deliverable 4.1.

4.1 Product Category Rules

4.1.1 Functional Unit

The definition of functional unit described in the document from the European Commission remains the same as it was reported in the previous deliverable: “one kWh of the total energy provided over the service life by the battery system, measured in kWh”, where the total energy is the total amount of electricity provided by the battery over its service time [12]. The definition of total energy was updated from the earlier version of the European Commission’s document, defining different approaches on how to quantify it [12]. In the previous version, the document described two different approaches based on two different definitions of service life, while the updated version defines the total energy provided depending on the vehicle category. The final document [12] considers four different categories:

- Light-duty EV batteries
- Category L (Motorcycle) EV batteries
- Medium duty and heavy-duty EV batteries
- Other EV batteries

Since the former two categories do not describe any application assimilable to the object of this study, the definition of their service life is not being reported in this document.

The definition of the reference flow was not changed in the newer version. The reference flow is 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[12].

Medium duty and heavy-duty EV batteries

For EV batteries installed in medium-duty and heavy-duty vehicles (categories M2, M3, N2 and N3 in the meaning of the Regulation (EU) 2018/858) the total energy shall be calculated by multiplying (a) the service life (expressed in number of full cycles equivalents) with (b) the battery energy capacity. The service life is defined as the total number of full equivalent discharge cycles (i.e., from 100% SoC to 0% SoC until the end-of-life of the battery) as declared by the CFB declarant, equivalent to the expected lifetime in terms of cycles as to be declared according to Annex IV of the Battery Regulation Proposal [15]. Documentation in support of the claim (declared lifetime, total energy throughput and methods / standards used for determining it) shall be provided in the CFB supporting study. The battery energy capacity is calculated as the rated capacity (expressed in “Ah”, according to Annex IV of the Battery Regulation Proposal [15]) multiplied by the nominal voltage (expressed in “V”, according to Annex XIII of the Battery Regulation Proposal [15]). This parameter

corresponds to the full dischargeable electrical energy (expressed in kWh), from 100% State of Charge (SoC) to 0% SoC, at Beginning of Life (BoL).

Other EV batteries

For EV batteries belonging to category O in the meaning of the Regulation (EU) 2018/858 and for all other EV batteries under Article 7 of the Battery Regulation Proposal [15] not falling under the previous cases, the total energy (in kWh) shall be calculated by multiplying (a) the service life in cycles with (b) the average amount of delivered energy over each cycle. The service life is defined as in Article 10 Annex IV of the Battery Regulation Proposal [15] as the expected lifetime under the reference".

Directives from the Global Battery Alliance [14] were updated to comprehend the end-of-life and recycling of the battery, while previously only covering cradle-to-gate assessments.

4.1.2 System boundary

In [12] the definition of the system boundaries remains unchanged, with the main stages being identified as:

- “Raw materials acquisition and pre-processing”
- “Manufacturing” of the battery
- “Distribution”
- “End-of-life”

In the frame of the “raw material acquisition and pre-processing” stage, a slight modification was made. While the previous version “packaging production” of raw materials was to be included in this stage, the newer version does not mention it as a requirement for the modelling.

Considering the “manufacturing” stage, a specification as to what the final battery consists of was added, stating that the final battery comprises all components that are contained in or attached to the battery housing [12].

As previously mentioned, the main update in [14] concerns the end-of-life and recycling. The updates concerning recycling will be further analysed in the section concerning the end-of-life phase of the life cycle inventory.

4.1.3 Life Cycle Inventory

Manufacturing

In [12] the “Manufacturing” section has been updated with more precise definition of what is part of the battery and what should be added to the inventory, stating that “the final battery comprises all components that are contained in or attached to the battery housing”. Following this definition, the “Manufacturing” life-cycle stage shall include:

- Anode and cathode active material production.
- Anode and cathode production, including the mixing of ink components, coating of ink on collectors, drying, calendaring, and slitting.
- Electrolyte production, including the electrolyte salt mixing.
- Housing and cooling system assembling

- Cell production (i.e., the assembly of cell components into a battery cell), including stacking/winding of electrodes and separator, assembly into a cell housing or pouch, injection of electrolyte, injection of the electrolyte, closing of cell, testing and electrical formation.
- Module assembling, i.e., assembly of cells into modules/pack including electric/electronic components, housing, and other relevant components.
- Battery assembly, i.e., assembly of modules with electric/electronic components, housing, and other relevant components into a finished battery
- All transport operations of the final and intermediate products to the site where they are used.

The remaining documents consulted did not receive any modification concerning the “manufacturing” stage of the LCI.

Distribution

In [12] the definition of the “Distribution stage” has been updated to state more clearly which are the boundaries of such stage: the “distribution” stage shall consider the transport of the battery from the manufacturing site to the final assembly of the battery within the vehicle. This was previously identified as “final use site” or “reference entry point into the market”.

End-of-life

The “end-of-life” stage was the section that received the most attention and updates in the documents considered. Recycling is in fact the focus of the updates in the Global Battery Alliance Rulebook [14], while the majority of modifications in [13] concern the allocation rules to be used while modelling end-of-life and recycling.

In [12] is stated that the “end-of-life” stage begins when the product in scope (or the EV where the battery is incorporated) is disposed of or discarded by the user and ends when the product in scope is returned to nature as a waste product or enters another product’s life cycle (i.e., as a recycled input). Moreover, it is also specified that wastes produced during previous stages (e.g. “Raw material acquisition and pre-processing” and “manufacturing”) shall be included in the life cycle analysis and modelled at the stage where the waste is produced.

The document also added a clearer definition of what shall be included in the “end-of-life” section:

- Battery waste collection
- Battery dismantling
- Thermal or mechanical pre-treatment (e.g., milling of the battery cell)
- Separation and conversion into recycled material (e.g., pyrometallurgical and hydrometallurgical treatment)."

It is emphasized the use of the Circular Footprint Formula (CFF) to assess environmental impacts during these stages. It is specified that the recycled material content must be calculated based on traceable evidence throughout the supply chain, and the “end-of-life” stage modelling shall adhere to specific default parameters, including collection rates and recycling processes. These parameters are reported in the annexes of the document [12]. It is also specified that the use of custom collection rates or recycling processes may

be permitted, provided that verifiable evidence is supplied to demonstrate a link to the specific battery models concerned. Default parameters to be used are then detailed. The default collection rate and recycling process are to be used unless company-specific data is available; for deviations from defaults, companies must demonstrate traceability and compliance with specific recycling facilities or processes.

It is finally stated that the application of the CFF must account for both recycled content and EOL impacts, ensuring consistency with the general Environmental Footprint (EF) method [12].

The main updates on recycling in [14] concern allocation. Specific allocation rules and parameters are given for each potential dismantling and recycling process and route, comprehending electrical deactivation of the spent battery, disassembly of the battery pack into modules or cells, pyrolysis (high temperature treatment >200 °C), mechanical, pyrometallurgical, and hydrometallurgical processes. The overall indications to manage allocations have not changed and can be consulted in Deliverable 4.1.

[13] was updated to reflect the indications stated in [14], taken as a model to form rules on end-of-life and recycling modelling.

Allocation rules

CFP Rules [12] have been updated clearly stating a decision hierarchy to follow when dealing with multifunctional systems:

1. Subdivision
2. Allocation based on a relevant underlying physical relationship (mass or energy)
3. Economic allocation

For economic allocation, the following rules shall apply:

- Economic allocation shall be applied when the price difference between the different outputs is higher than a factor of four.
- Sixty months global price (or revenues, or costs) averages shall be used as minimum to assess price differences.
- All allocation factors, the approach for calculating them and the underlying data sources shall be disclosed in the CFB supporting study.
- If the process has been operative for shorter time, a shorter timespan (min 1 year) may be used if duly justified in the CFB supporting study. In this case, the CFB shall be updated at the latest when 5 year average values are available.

The paragraph dedicated to economic allocation involving precious metals as outputs has been deleted, since the new general indications for economic allocation are valid for their specific case as well.

Allocation and modelling rules for battery housing in EV batteries was also updated, now providing indications in case of virtual housing approach, and clearer criteria to determine whether the battery housing is considered to provide additional functions or not. It is stated that battery housing is considered to provide additional functions if it contributes to the torsional stiffness and the crash resistance off the vehicle. In the context of the CFB and for the sake of verification, the sole torsional stiffness shall be considered to identify

whether the battery housing provides additional functions or not. For this purpose, the CFB applicant shall report two values of torsional stiffness of the vehicle in the CFB supporting study: i) with battery housing and ii) without battery housing. If the torsional stiffness with battery housing is higher than the stiffness without battery housing, then the battery housing is contributing to the stiffness of the vehicle and thus it can be considered as providing additional functions to the vehicle.

Electricity modelling

Extensive guidance on how to model production of electricity in LCA is provided in [12]. General rules and hierarchy are coherent with past versions, while the criteria to be followed when dealing with supplier-specific electricity production have been updated:

- *Criterion 1 - Convey attributes.* To satisfy the criterion, the contract must state the product's energy source mix and explain how this mix is calculated.
- *Criterion 2 - Be a unique claim.* The contractual instrument must ensure exclusivity of environmental claims through verified mechanisms such as audits to prevent double-claiming, while tracking and managing its lifecycle via audits, third-party systems, or registries. It must link the electricity quantity to a country-specific residual consumption mix, publicly disclosed by authorities, accounting for regional variations and coexisting tracking systems. Additionally, the instrument must unambiguously identify the generation facility's technology, age, location, and capacity, and require the facility to operate in a country with a compliant tracking system meeting Criterion 3 standards.
- *Criterion 3 - Be issued from a tracking system that fulfils specific criteria.* The contractual instrument must originate from a tracking system meeting specific criteria: it must operate objectively, transparently, and without discrimination in certificate issuance, while being uniquely government-appointed per geographical area and energy type. The system requires fraud-resistant mechanisms for certificate handling, independence from verifiers and energy market entities, and transparent governance with judicial oversight. Its use must be legally enforceable to validate energy origin claims and coordinate with authorities to prevent double-counting of renewable/environmental attributes.
- *Criterion 4 - Be as close as possible to the period to which the contractual instrument is applied.* The contractual instrument shall ensure that certificates are valid no longer than 12 months after the represented electricity was generated. This means that the certificate shall be used (hence cancelled/redeemed/retired) within 18 months after the electricity was generated.
- *Criterion 5 - Be sourced from the same market in which the reporting entity's electricity-consuming operation are located and to which the instrument is applied.* The contractual instrument and the company claiming it must operate within shared "market boundaries," defined as an area where the electricity generation and consumption points are physically interconnected (with cross-grid coordination if applicable). These boundaries require mutual recognition of energy tracking systems between participating countries/utilities and mechanisms to prevent double-counting of claims.

Moreover, indication on how to model the average consumption mix was added. The average consumption mix shall be modelled with a secondary dataset. If the node dedicated to the CFB in the Life Cycle Data Network includes a dataset modelling the average consumption mix in the country, or in the region (EU) of interest, that dataset shall be used giving priority first to the country, and then to the region. Otherwise, the

global electricity consumption mix registered in the node dedicated to the CFB in the LCDN shall be used [12].

Global Battery Alliance [14] indications remained almost unchanged, keeping the two previous set of calculation rules: the Harmonized Market Approach (HMA) and the Physically Modelled Approach (PMA).

Life Cycle Impact Assessment (LCIA)

No changes were made for LCIA in these documents, climate change is the only impact category considered [12], [13], [14].

5 LCA of on-board energy storage systems

The present chapter is organized according to the four phases of the LCA methodology [2], [3]. Paragraph 5.1 describes the goal and scope (Phase 1). The goal definition sets the context of the LCA study and is the basis of the scope definition which frames and outlines the assessment in terms of defining the functional unit, system boundaries, data quality requirement, the impact categories to be assessed, etc. Following the definition of goal and scope, the inventory analysis (Phase 2, Paragraph 5.2) collects information about the physical flows in terms of input of resources, materials, semi-products and products and the output of emissions, waste and valuable products for the product system. The outcome of the inventory analysis is the life cycle inventory, a list of quantified physical elementary flows for the product system that corresponds to the provision of the service or function described by the functional unit. Taking the life cycle inventory as a starting point, the impact assessment translates the physical flows related to the product system into impacts on the environment using knowledge and models from environmental science (Phase 3, Paragraph 5.3). The interpretation is the phase of the LCA in which the results obtained in the inventory analysis and life cycle impact assessment phases are combined to draw conclusions and recommendations consistent with the goal and scope of the study (Phase 4, Paragraph 5.3).

5.1 Goal and Scope definition

5.1.1 Goal definition

The goal of the LCA study described in this report is to evaluate the environmental sustainability of adopting hybrid energy storage systems, which combine battery energy storage systems with SC or SMES, in marine applications selected within WP1 [16]. SCs and SMESs are high-power ESS technologies that can be considered instead of batteries to fulfil the vessel power requirements. This assessment is conducted in comparison to reference cases (also identified in WP1) representing the traditional solution based only on BESS.

5.1.2 Scope definition

This paragraph describes the product systems under analysis, both in the reference configurations and in the configurations investigated within the V-ACCESS project, as well as all methodological assumptions underlying the LCA study. Specifically, these assumptions relate to the definition of the function, the functional unit and the reference flow, the determination of the system boundaries, as well as the selection of the impact categories, etc.

Description of the case studies

Reference case studies

1. Electric ferry

Electric ferry is a fully electric double-ended roll-on/roll-off vessel with an overall length of 74 m and a breadth of 15 m. The ferry is used for commuting between two islands with around 30 minutes of travelling time. The ferry reference case is equipped with a symmetrical (redundant) electric power system including two identical BESS as main energy source. The BESS is based on Lithium-ion technology (G/NMC-P Orca Energy from Corvus Energy) and can be charged from an external power source (plug-in hybrid electric). The

main technical characteristics of the BESS technology are recapped in **Errore. L'origine riferimento non è stata trovata..**

2. Offshore Supply Vessel – Active Heave Compensation (OSV-AHC)

Reference case

The Offshore Support Vessels (OSV) with Active Heave Compensation (AHC) System (OSV-AHC) is a ship specially designed to supply offshore oil and gas platforms and other offshore installations. It is characterized by an overall length of 94 m and a breadth of 21 m.

The OSV-AHC reference case is equipped with a hybrid marine power system composed of three identical 2.457 MW diesel engines and a BESS used only for Dynamic Positioning (DP) operations with high C-rate and nominal energy. The BESS is based on Lithium-ion technology designed for high power demands (Lithium iron phosphate (LFP) technology from Saft's Seenergy^{®1}). The OSV-AHC operates 219 days per year.

3. Stern trawler

A stern trawler is a vessel mainly used for fishing and its typical operating cycles include high power peaks during shooting and heave of the trawl. Trawler is characterized by an overall length of 80 m and a breadth of 17 m. The trawler reference case is equipped with a hybrid marine power system composed of a 4,800 kW diesel engine and a BESS used during trawling, transit and unloading in port. The BESS is based on Lithium-ion technology designed for high power demands (LFP technology from Saft's Seenergy[®]).

The selection of these ship types is justified by their diverse operational profiles and specific applications of energy storage system, as detailed in [16]. Ferries, operating on short and regular routes, are particularly suitable for full electric propulsion and frequent recharging in port, enabling zero-emission operation. OSV-AHC utilize EES mainly for dynamic positioning, where high-power support over limited durations improves fuel efficiency and reduces emissions. Trawlers represent a hybrid application, where EES supports various phases, such as trawling, transit, and unloading, optimizing engine load and minimizing fuel consumption. These three ship types provide representative use cases for assessing the integration and benefits of EES in maritime transport.

V-ACCESS case studies

The V-ACCESS case studies consider the installation of SC or SMES (high-power ESS) technologies to support BESS in the electric ferry, OSV-AHC and stern trawler. SC and SMES devices are developed, respectively, by the V-ACCESS technology providers Skeleton⁺² and ASG superconductors³. The main technical characteristics of Li-ion batteries, SC and SMES are illustrated in **Errore. L'origine riferimento non è stata trovata..**

¹ <http://www.ocean-drilling.com/index.php?c=show&id=29>

² <https://www.skeletontech.com/>

³ <https://www.asgsuperconductors.com/>

Table 3. Main technical characteristics of the V-ACCESS ESS technologies (data provided by WP1).

Technology	Li-ion Batteries		Higher Power Tech.	
	G-NMC/ Power	G-LFP/Power	Super Capacitor	SMES
Reference Module	Orca Energy	Seanergy 48P Module	SkelMod162V62F	741 kJ (200kW-2.5s)
Manufacturer	Corvus Energy	Saft	Skeleton	ASG Superconductors
Capacity [Ah]	120	60	2.021	0.275
Nominal Energy [kWh]	5.65	2.6	0.226	0.206
Voltage nominal [V]	47.2	46.2	121,5	750
Discharge Current rate [C-rate] (cont./10s peak)				121 (28s)
Charge Current rate [C-rate] (cont./10s peak)	3 / 5	4 / 5	114 / 1376	970 (2.5s)
System Specific Energy [Wh/kg]	76	51	4.1	1670 (peak)
System Energy Density [Wh/dm ³]	85	66	2.8	0.206
System Cost per energy unit [Euro/Wh]	0.9	0.4	5	0.666
Specific Power [W/kg] (peak, 50%SoC)	380	255	5642	144
Power Density [W/dm ³] (peak, 50%SoC)	425	330	3853	345
Calendar Life, 20°C @EOL (80%SOH)	20 years	20 years	28 years	Negligible
Cycle life to 80%SOH.	8000 cycles @80%DoD, 1.2C/1.2C, 25°C	6000 cycles @80%DoD, 0.4C/0.4C, 25°C	1.000.000 @75% DoD, 15C/15C, 35°C	Negligible

The V-ACCESS case studies were defined as part of the research activities carried out in WP1, where a preliminary assessment of combined storage systems for the selected marine applications was conducted. The results of this assessment, including the installed ESS capacity, energy throughput, and the power distribution between the BESS and HP-ESS (SC and SMES), are presented in Paragraph 5.2. For more detailed information, refer to Deliverable D1.2, titled 'Preliminary Assessment of Combined Storage Systems for the Selected Marine Applications.'

Function, functional unit and reference flow

The functions of the examined system are described in Paragraph 5.1.2, while the functional unit (FU) selected for each case study is detailed in the following. For each case study, the FU is the service provided (mission profile) by the ESS, based on an assumed ship lifetime of 30 years:

- Electric ferry: the power system (BESS in the reference case and HESS in the V-ACCESS case studies) provides the energy for the propulsion of the ferry operated 16 h per day and 320 days per year considering an operational lifetime of 30 years. Four fundamental cycles per day, 16 turn/return trips per day between stops A and B. (Energy consumption provided by WP1). Hence the FU is 77.44 GWh over a 30-years operational lifetime.
- OSV-AHC: the power system (ICE and BESS in the reference case and ICE and HESS in the V-ACCESS case studies) provides the energy required for the dynamic positioning operations. The OSV-AHC is assumed to operate 219 days per year over an operational lifetime of 30 years. The FU is then 9.48 GWh over a 30-years operational lifetime.
- Trawler: the power system (ICE and BESS in the reference case and ICE and HESS in the V-ACCESS case studies) provides the energy required for trawling, transit and unloading in port. The OSV-AHC operates 240 days per year over an operational lifetime of 30 years. The FU is then 5.09 GWh over a 30-years operational lifetime.

The reference flow, i.e. the amount of product system needed to realise the FU, includes all components that provide the function described by the FU, i.e. the lithium-ion batteries, the SC and the SMES. The installed capacity and the energy required for each mission profile were derived by WP1.

System boundaries

The system boundaries for the modelling of ship power systems follow a “cradle-to-grave” approach (from raw material extraction to end-of-life treatment). The life cycle stages, and process units included in the analysis are illustrated in Figure 1 and Figure 2 and described below:

- Construction phase: this phase encompasses the entire production process from raw material acquisition, including extraction and processing, up to the production of individual HESS components (active material, separator, electrolyte, cell casing, superconducting coil, etc.) and the final assembly of the product system. This phase also includes the production process of the ESS (BESS and SC) that need to be replaced within the considered timeframe. The ESS end-of-life criterion has been based on system capacity loss, with a fixed value of 20% capacity loss considered for NMC and SC technologies. SMES is characterized by very low or no degradation regarding capacity loss, so the SMES capacity fade has been neglected. Consequently, SMES does not require replacement.
- Operational phase: this phase includes the energy required by each vessel to perform its function in a time scale of 30 years. It includes the energy required to perform the vessel mission, the energy losses due the ESSs efficiency and the energy for cooling them.
- End-of-life phase: the recycled content approach has been adopted for the end-of-life phase, considering the environmental benefits associated with the recycled material content. Consequently, benefits related to the availability of recyclable materials at the end of the useful life of the ESSs have not been included, as this would result in double counting of environmental benefits.

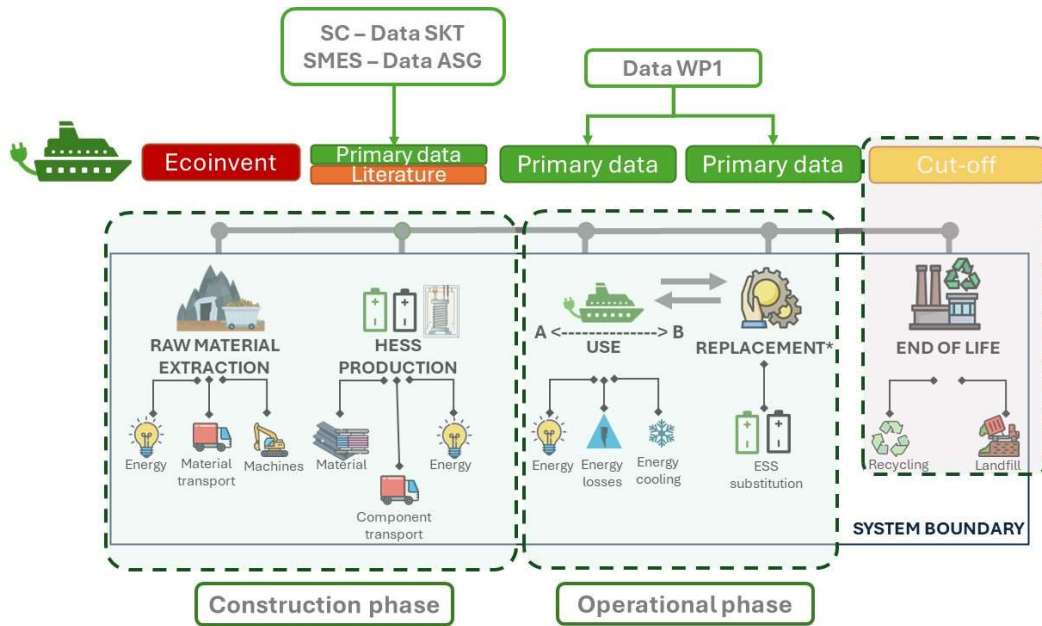


Figure 1: System boundaries for the electric ferry case (HESS: Hybrid Energy Storage System; ESS: Energy Storage System; SC: supercapacitor; SKT: Skeleton; SMES: superconducting magnet energy storage; ASG: ASG Superconductors S.p.A.; WP: Work Package; *Replacement occurs during the operational phase, but the production and assembly of replacement components are included in the construction phase)

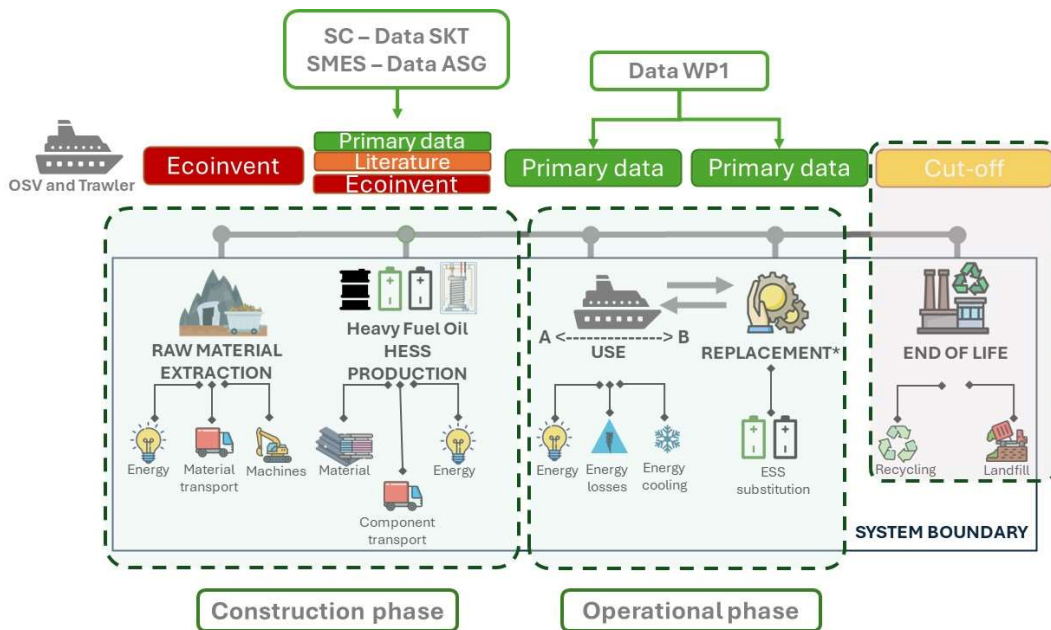


Figure 2: System boundaries for the OSV – AHC (Offshore Service Vessel - Active Heave Compensation) and Trawler cases (The acronyms have the same meaning as explained in Figure 1). *Replacement occurs during the operational phase, but the production and assembly of replacement components are included in the construction phase.

Life Cycle Impact assessment method

The environmental impact assessment was carried out using the Environmental Footprint – EF 3.1 method [17], which incorporates updates to the environmental footprint methods in accordance with EU/2021/2279 recommendation by the European Commission [18]. In this study, the analysis was limited to impact categories whose characterization models are classified with a reliability level of I (recommended and satisfactory method) and II (recommended method, but requiring some improvements), while impact categories with a reliability level of III (recommended method, but to be applied with caution) were not analysed. The only exception was made for the category related to the impact on the consumption of mineral and metallic resources, which, despite having a reliability level of III, was analysed due to the dependence of electrochemical storage technologies on minerals and metals [19]. Since the resource use impact category in the EF method has a reliability level of III, the impact on resource consumption was further evaluated using an alternative approach, namely the Life Cycle Commodities Costing (CLCC) method [20].

The selected environmental impact categories used to describe the system's performance are listed in Table 4.

Table 4: Selected environmental impact categories and the corresponding reliability level within the EF 3.1 method [17].

Environmental impact categories [reliability level]	Impact category indicator (Acronym)	Unit
Acidification [II]	Accumulated exceedance (A)	mol H ⁺ eq
Climate change [I]	Global warming potential (GWP)	kgCO ₂ eq
Particulate matter [I]	Impact on human health (PM)	Disease incidence
Eutrophication, marine [II]	Fraction of nutrients reaching marine end compartment – N (EU _M)	kg Neq
Eutrophication, freshwater [II]	Fraction of nutrients reaching freshwater end compartment -P (EU _{FW})	kg Peq
Eutrophication, terrestrial [II]	Accumulated Exceedance (EU _T)	mol Neq
Ionising radiation, human health [II]	Human exposure efficiency relative to U ²³⁵ (IR)	kg of uranium-235 equivalents (kg U ²³⁵ eq)
Ozone depletion [I]	Ozone Depletion Potential (ODP)	kg of trichlorofluoromethane) equivalents (kgCFC-11eq)
Photochemical ozone formation, human health [II]	Tropospheric ozone concentration increase (POF)	kg Non-Methane Volatile Organic Compounds equivalent (kg di NMVOCeq)
Resource use, minerals and metals [III]	Abiotic resource depletion, ultimate reserves (ADP)	kg of antimony equivalents (kg Sbeq)

The commodity life-cycle cost (CLCC) indicator is an economic indicator developed by Mela et al. [20]. It aims to quantify the consumption of natural resources by a product or process throughout its life cycle. This indicator should be seen as a complement to the LCA, which, being expressed in monetary units, can facilitate the decision-making process. The indicator has been modified and improved since it was first developed in 2021: see [21] and [22] for more details. The indicator is open-source, and it can be computed using a dedicated R package [21].

Other resource depletion indicators relying on monetary units do exist, among which ReCiPe [23] represents one of the most widely spread. However, the ReCiPe method [24] is based on the concept of extraction cost which, in turn, relies on the concept of diminishing marginal returns of a finite natural resource: extraction

cost increases with the demand and exploitation of the resource itself. As highlighted by [25], however, extraction cost is a static measure of scarcity as it does not take into account factors that, in the future, could influence the ease of extraction of a given resource or its abundance. Additionally, using this approach, only supply-side information is used to estimate resource scarcity, while variations in demand can also have a significant impact on it.

Market price, on the other hand, incorporates information both on current demand and, albeit partially, on the expectations of economic operators regarding future demand, and therefore fully corresponds to the “perfect” measure of natural resource scarcity provided by [26]:

“A measure of scarcity must be characterized by an essential property: it must be able to synthesize all the sacrifices - direct and indirect - sustained to realize a unit of the resource.”

The definition does not refer only to the supply side, as it might seem at first glance. In fact, the “sacrifices sustained” also imply the willingness to pay, which is a demand-related factor; while “indirect costs” can be interpreted as the lack of future consumption, a consequence of present consumption. [26] also highlights that extraction costs do not include this indirect component and that market prices should be preferred as a measure of resource scarcity also because they are linked, at least in the medium term, to stocks.

The limit of market prices lies in the market itself, which is not always able to consider the environmental effects of resource use, i.e., the so-called environmental externalities. It is therefore necessary, concludes [26], to correct the market price to account for the consumption of common property natural resources.

The CLCC indicator was developed from the concept of basic raw material cost, which is the cost of all natural resources acquired and used in the production phase of a given [27]. However, this concept is extended to the entire life cycle to obtain an indicator - the CLCC - that represents a measure of the extent to which a product/process uses natural resources.

The use of natural resources is quantified from a physical perspective with the LCA analysis and from an economic perspective through average market prices. Market prices can be considered a measure of scarcity [28], [29], provided they are observed over a sufficiently long period. Measuring the use of natural resources by a product is very important for developing and implementing policies aimed at promoting sustainable development.

The starting point is the list of all material and energy flows of the SimaPro software inventories. For each material or energy flow, the corresponding market price was identified using only open-source data sources. In summary, the CLCC indicator quantifies, under an economic point of view, the consumption of natural resources by a product/service during its life cycle, starting from physical material flows and using market prices as characterization factors, assuming that market prices (if properly calculated on adequately long-time spans) contain information on the current and future availability of the resource (at least in the medium-term).

An alternative version was also developed, based exclusively on so-called “critical materials”: those materials of fundamental importance to produce a large number of goods, but at the same time characterized by a very concentrated supply in a few countries, often with high geopolitical risk. The list of critical materials developed by the European Commission in 2011 [30], and subsequently expanded, was the starting point for defining this additional indicator. The methodology used by the European Commission to identify critical materials is available in [31], while the latest version of the list of critical materials is provided by [32].

5.2 Life Cycle Inventory

In the Life Cycle Inventory (LCI) analysis phase, the primary data required for modelling the foreground processes and the datasets for the background processes were collected and processed. Primary data were mainly gathered on the technical characteristics, constituent materials, and the energy required for manufacturing the SC and SMES systems, as reported by the technology providers Skeleton⁺ and ASG Superconductors and data related to the installed energy capacity and energy consumption during the operational phase, provided by WP1 which simulated several configurations.

The selection of environmental datasets involved two steps: first, identifying the most appropriate datasets available, and second, adapting these datasets to best match the specific product system under consideration. In cases where a dataset is missing, the most similar one is used as a proxy. The Ecoinvent 3 database (version 3.9.1) [4] was used to model the background processes, adopting the cut-off (or recycled content) approach.

In the following section, the authors outline the procedure and assumptions used to compile the LCI of the examined case study, integrating primary data with literature sources and data from the Ecoinvent database.

5.2.1 Battery energy storage system technology: NMC-G Lithium-ion and Lithium iron phosphate

The LCI of NMC-G and LFP lithium-ion battery technologies was developed based on the main technical specifications provided in WP1, summarized in Table 4, and datasets available in the Ecoinvent database [33]. The manufacturing process of the NMC-G lithium-ion battery was modelled using the Ecoinvent dataset: *“Battery, Li-ion, NMC111, rechargeable, prismatic {CN} | battery production, Li-ion, NMC111, rechargeable, prismatic | Cut-off, U.”* The inventory is modelled for China and is based on the publication by Dai et al. [34], describing cells composed of a nickel-manganese-cobalt (NMC111) cathode, a graphite-based anode, a liquid electrolyte, and a porous plastic separator. Similarly, the manufacturing process of the LFP battery was modelled using the Ecoinvent dataset: *“Battery, Li-ion, LFP, rechargeable, prismatic {GLO} | market for battery, Li-ion, LFP, rechargeable, prismatic | Cut-off, U.”* The inventory is modelled for a global scale, though LFP batteries are mainly produced in China. Both datasets were adjusted to align with the specific product system under consideration. More detailed information on the modelling of both technologies is provided in the appendix (Chapter 9, Paragraph 9.2).

The operational phase is linked to the specific application within the V-ACCESS case studies and is detailed for each case in the following sections (Paragraph 5.2.3 for the electric ferry, Paragraph 5.2.4 for the OSV-AHC and Paragraph 5.2.5 for the trawler).

Concerning the EoL, as a first approximation, it is assumed that BESSs are fully recyclable. In accordance with the 'Recycled Content, Cut-Off' approach, this means that recyclable materials are cut off from the producing product system, i.e., they are removed burden-free from the production activity, and no environmental impacts or benefits are allocated to them [33]. The environmental impacts and benefits associated with the recycling processes are attributed to the second-life uses of the recycled materials in a subsequent system.

5.2.2 High power energy storage technologies: supercapacitor and superconducting magnetic energy storage systems

The LCIs of SC and SMES technologies manufacturing processes were developed based on primary data regarding technical characteristics, constituent materials, and the energy required for manufacturing, as provided by the technology providers Skeleton⁺ and ASG Superconductors, respectively. These data were supplied through dedicated data collection questionnaires developed by RSE and Polimi (Milestone M4.1). Table 5, Table 6 and Table 7 provide the inventory data for modelling the key manufacturing processes of an SC rack with a rated energy capacity of 2.26 kWh, along with its SC module rack subcomponent and SC cell module subcomponent. These tables are based on primary data provided by Skeleton⁺ and are elaborated with the support of relevant LCI datasets from Ecoinvent and additional adaptations. For a more detailed explanation of the data sources and assumptions, please refer to Appendix 9.2.

Table 5 presents the inventory data for the manufacturing process of the SC rack, including materials such as the supercapacitor modules and other components like the BMS, cooling system, and cabinet.

Table 5 - Inventory data for modelling the manufacturing process of a SC rack with a rated energy capacity of 2.26 kWh, weight 550 kg (own elaboration based on Skeleton primary data).

Material/component	Value	LCI modelling datasets (Ecoinvent & own adaptation)
Supercapacitor modules (10 modules) (kg)	330	Own elaboration based on information provided by Skeleton (Table 6)
Other component (BMS, cooling system, cabinet, switch gear) (kg)	220	Own elaboration based on the information provided by Skeleton, with reference to relevant literature

Table 6 outlines the inventory data for the manufacturing process of the SC module, which includes the supercapacitor cells and the module casing. Table 7 details the inventory data for the manufacturing process of a single SC cell, including materials such as the positive and negative electrode paste (activated carbon-based), substrates, separator, and electrolyte, as well as energy and waste treatment data. The waste treatment refers to the processing of production waste generated from the manufacturing of the supercapacitor cells.

Table 6 - Inventory data for modelling the manufacturing process of a SC module, weight 33 kg (own elaboration based on Skeleton primary data).

Material/component	Value	LCI modelling datasets (Ecoinvent & own adaptation)
Supercapacitor cells (54 cells) (kg)	27	Own elaboration based on information provided by Skeleton (Table 7)
Module casing (kg)	6	Battery module packaging, Li-ion {GLO} market for battery module packaging, Li-ion Cut-off, U (proxy for SC module casing)

Table 7 - Inventory data for modelling the manufacturing process of a SC cell, weight 0.54 kg (own elaboration based on Skeleton primary data).

Material/component	Value	LCI modelling datasets (Ecoinvent & own adaptation, see Appendix 9.2)
Positive electrode paste (activated carbon based) (kg)	0.070	Own elaboration based on information provided by Skeleton (see Appendix 9.2)
Positive electrode substrate (kg)	0.030	Aluminium collector foil, for Li-ion battery {GLO} market for aluminium collector foil, for Li-ion battery Cut-off, U (proxy for aluminium precoated foil)
Negative electrode paste (activated carbon based) (kg)	0.056	Own elaboration based on information provided by Skeleton (see Appendix 9.2)
Negative electrode substrate (kg)	0.030	Aluminium collector foil, for Li-ion battery {GLO} market for aluminium collector foil, for Li-ion battery Cut-off, U (proxy for aluminium precoated foil)
Cellulose separator (kg)	0.017	Kraft paper {RoW} market for kraft paper Cut-off, U (proxy for cellulose)
Electrolyte (kg)	0.172	Acetonitrile {GLO} market for acetonitrile Cut-off, U
Cell container	0.125	Own elaboration based on information provided by Skeleton (see Appendix 9.2)
Energy: electricity/heat		
Electricity for cell assembly (kWh)	5	Electricity, medium voltage {DE} market for electricity, medium voltage Cut-off, U
Waste treatment		
Treatment of production waste from supercapacitor cells	0.035	Waste electric and electronic equipment {GLO} market for waste electric and electronic equipment Cut-off, U

The SMES system is composed of various key components (Table 8). The core of the system includes a superconducting coil supported by a mandrel (stainless steel). The superconducting coil consists of magnesium diboride (MgB₂) as the primary superconducting material, with additional components such as Monel and Nickel (Ni) for structural and protective purposes. To maintain the necessary cryogenic conditions, the cryostat consists of a stainless-steel vacuum chamber with multi-layer insulation (cryogenic insulation⁴) and a vacuum pump (weight 5 kg, type Pfeiffer Duo M20⁵). The multi-layer insulation is made of a superinsulation composed of 10 layers of polyester foil, double-sided aluminized, perforated, and interleaved with 10 layers of knit-woven polyester spacer material. In the LCA model, polyester dataset was used as a proxy.

The cooling system comprises a cryocooler, a compressor (weight 100 kg, type F-70 Indoor Water-Cooled Compressor⁶), and a chiller (200 kg) to ensure stable low-temperature operation. The cryocooler was modelled based on the information provided by ASG Superconductor, who selected the Cryocooler RDK415D⁷ within the V-ACCESS project. The water-cooled compressor was modelled using a dataset for an air compressor, screw-type, as a proxy, due to the unavailability of a specific dataset for the water-cooled compressor in the database. The unit of compressed air (0,71 p) was calculated based on the weight of the

⁴<https://www.beyondgravity.com/en/satellites/thermal-control-solutions/cryogenic-superinsulation#COOLCAT-Multi-Layer-Insulation>

⁵ https://www.pfeiffer-vacuum.com/global/en/shop/categories/DUO_20

⁶ <https://shicryogenics.com/product/f-70-indoor-water-cooled-compressor-series/>

⁷ <https://shicryogenics.com/product/rdk-415d2-4k-cryocooler-series/>

compressor in the Ecoinvent database (140 kg), in comparison with the weight indicated by ASG for the water-cooled compressor (100 kg). The chiller was modelled using the Refrigerator {GLO} | market for refrigerator | Cut-off, U dataset. The quantity (unit) of the refrigerator was calculated based on the weight of the refrigerator in the Ecoinvent database (60 kg), in comparison with the weight indicated by ASG for the chiller (200 kg). The current lead assembly integrates copper conductors (5 kg) with bismuth strontium calcium copper oxide (BSCCO) superconducting wires (0.05 kg). Additional heat conduction plates (50 kg of copper) help manage thermal dissipation. Mechanical supports are made from stainless steel, copper, and fiberglass epoxy (G10) to provide structural integrity. Table 8 presents the inventory data for modelling the main manufacturing processes of an SMES with a rated energy capacity of 200 Wh. For more detailed information on LCA model, refer to Appendix 9.2.

Table 8 - Inventory data for modelling the manufacturing process of a SMES with a rated energy capacity of 200 Wh, weight approximately 1000 kg (own elaboration based on ASG Superconductors primary data).

Material/component	Value	LCI modelling datasets (Ecoinvent & own adaptation, see Appendix 9.2)
Cryostat (cryogenic box with vacuum and insulating layers)		
<i>Stainless steel (kg)</i>	400	Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U
<i>Multi-layer thermal insulation (kg)</i>	1	Fibre, polyester {GLO} market for fibre, polyester Cut-off, U (proxy for multi-layer thermal insulation)
<i>O-ring (kg)</i>	0.1	Acrylonitrile-butadiene-styrene copolymer {GLO} market for acrylonitrile-butadiene-styrene copolymer Cut-off, U
<i>Vacuum pump (unit)</i>	2	Pump, 40W {GLO} market for pump, 40W Cut-off, U
Current lead		
<i>Copper (kg)</i>	5	Copper, cathode {GLO} market for copper, cathode Cut-off, U
<i>Superconducting wire (Bismuth strontium calcium copper oxide - BSCCO) (kg)</i>	0.05	Own elaboration based on information provided by ASG Superconductors (see Appendix 9.2)
Heat conduction plate - Copper (kg)	50	Copper, cathode {GLO} market for copper, cathode Cut-off, U
Cryocooler (kg)	40	Own elaboration based on information provided by ASG Superconductors (see Appendix 9.2)
Water cooled compressor (F-70L - 7 kW) (kg)	0.71	Air compressor, screw-type compressor, 4kW {GLO} market for air compressor, screw-type compressor, 4kW Cut-off, U (proxy)
Chiller (unit)	3.33	Refrigerator {GLO} market for refrigerator Cut-off, U
Superconducting coil (MgB ₂) (kg)	200	Own elaboration based on information provided by ASG Superconductors (see Appendix 9.2)
Mandrel (kg)	60	Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U (proxy)
Mechanical supports		
<i>Stainless steel (kg)</i>	5	Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U
<i>Copper (kg)</i>	5	Copper, cathode {GLO} market for copper, cathode Cut-off, U
<i>Fiberglass epoxy - G10 (kg)</i>	1	Glass fibre {GLO} market for glass fibre Cut-off, U

Regarding the EoL, it is assumed, as a first approximation, that both the SC and SMES systems are fully recyclable. This assumption is consistent with the approach taken for BESS, following the 'Recycled Content,

Cut-Off' method. Therefore, recyclable materials are excluded from the production system, meaning they are removed from the production activity without any environmental burden, and no environmental impacts or benefits are allocated to them [33].

5.2.3 Electric ferry - LCI

The power system of the electric ferry for the reference case (BESS only) and the V-ACCESS case studies (BESS + SC and BESS + SMES) were designed based on logged data from their standard mission profile, provided by the V-ACCESS project partner Vard Electric (see Appendix A.3 of Deliverable 1.2). These data were used to determine the ESS requirements for both the reference case and the V-ACCESS case studies. In this full electric vessel, the BESS supplies all the vessel load.

In the reference case, the ferry's power system consists of two identical BESS units based on NMC-G lithium-ion technology, each with an installed energy capacity at the BoL of 678 kWh (totalling 2 x 678 kWh). Over the 30-year lifespan of the ship, the BESS units require two replacements. By the end of this period, the final battery packs retain 87.7% of their rated energy capacity.

In the V-ACCESS electric ferry case studies, a SC or SMES is integrated into the ferry's power system to supply high peak power, thereby relieving the battery from thermal and electrical stresses that accelerate degradation, ultimately increasing the useful life of the battery. Twelve V-ACCESS case studies are examined for the BESS-SC configuration and eight for the BESS-SMES configuration (see Table 9 and Table 10).

In the LCA model of the electric ferry reference case, the construction phase accounts for the environmental impact of manufacturing all BESS units required throughout the ship's lifetime. For the final battery packs, only a fraction of the manufacturing impacts is attributed to the case study, proportional to the effectively utilized capacity at the end of the ship's operational life relative to the remaining available battery capacity. Specifically, the BESS EoL criterion is based on system capacity loss, with a fixed threshold of 20% applied to Li-ion BESS technology.

The construction phase of the V-ACCESS electric ferry case studies includes the manufacturing process of both SC and SMES (see Paragraph 5.2.2), also accounting for the replacements needed during the ship lifetime. In detail, the same EoL criterion of BESS applies to SC, as reported by the technology provider Skeleton⁺, while for SMES, which exhibits little capacity degradation, as indicated by ASG Superconductors, capacity fade is considered negligible; therefore, no replacements are needed over the 30-year vessel lifetime. For all SMES components, a 30-year lifetime has been considered, except for the mandrel and the superconducting coil (MgB₂), for which, based on a communication from ASG Superconductors, a 40-year lifetime has been assumed.

The operational phase includes the electricity required for the vessel's mission, the energy losses associated with ESSs internal efficiency, and the additional electricity needed for cooling the ESSs. The operational phase was assumed to take place in Europe, and thus the average European electricity mix was used to model this life cycle stage.

The installed capacities at the BoL, the replacements of the ESSs, and the energy required for the mission, including losses due to efficiency and the energy required for cooling the ESSs, have been calculated and provided as part of the WP1 activities. The results obtained in WP1 for the reference case and for the BESS-SC and BESS-SMES V-ACCESS case studies are recapped, respectively, in Table 9 and Table 10. The reference case is the same for both BESS-SC and BESS-SMES V-ACCESS case studies.

Table 9 – Ferry case: BESS and SC installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1)

BESS Installed Energy at BOL [kWh] (number of modules)	SC Installed Energy at BOL [kWh] (number of modules)	Number of modules required for 30 years ship lifetime		Total Energy charged from shore for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including energy for cooling) [GWh]	Total energy consumption for cooling [GWh]	State of health at end of vessel lifetime [%]		Total Weight [ton]
		BESS	SC				BESS	SC	
678 x 2 (20s6p x2 = 240)	--	720	--	90.4005	12.9592 (14.34%)	4.2849 (4.74%)	87.7	--	17.916
	2.26 x 2; (5s2p x2 = 20)		40	90.1667	12.7254 (14.11%)	4.1940 (4.65%)	89.2	87.2	19.016
	4.52 x 2; (5s4p x2 = 40)		80	89.9610	12.5196 (13.92%)	4.1157 (4.575%)	90.6	86.3	20.116
	6.78 x 2; (5s6p x2 = 60)		180	89.7568	12.3155 (13.72%)	4.0390 (4.50%)	91.6	90.7	21.216
	9.04 x 2; (5s8p x2 = 80)		240	89.5839	12.1426 (13.55%)	3.9744 (4.44%)	92.5	94.0	22.316
	11.3 x 2; (5s10p x2= 100)		300	89.4136	11.9723 (13.34%)	3.9106 (4.37%)	93.7	91.2	23.416
644.1 x 2 (19s6p x2 = 228)	6.78 x 2; (5s6p x2 = 60)	684	180	90.3107	12.8693 (14.25%)	4.2376 (4.69%)	85.6	93.1	20.424
	9.04 x 2; (5s8p x2 = 80)		240	90.0133	12.5716 (13.97%)	4.1262 (4.58%)	87.3	98.5	21.524
	11.3 x 2; (5s10p x2= 100)		300	89.7994	12.3580 (13.76%)	4.0472 (4.51%)	88.86	91.2	22.624
621.5 x 2 (22s5p x2 = 220)	9.04 x 2; (5s8p x2 = 80)	660	160	90.4454	13.0041 (14.38%)	4.2800 (4.73%)	82.2	81.8	20.68
	11.3 x 2; (5s10p x2= 100)		300	90.1783	12.7370 (14.12%)	4.1818 (4.64%)	84.3	91.7	21.78
	13.65 x 2; (5s12p x2= 120)		360	89.9300	12.4887 (13.89%)	4.0905 (4.55%)	85.7	93.5	22.88
593.25 x 2 (21s5p x2 = 210)	13.65 x 2; (5s12p x2= 120)	630	360	90.4288	12.9874 (14.36%)	4.268 (4.72%)	78.8	93.5	22.21
	15.82 x 2; (5s14p x2= 140)		420	90.2563	12.8149 (14.20%)	4.2036 (4.66%)	80.5	93.9	23.31

Table 10 – Ferry case: BESS and SMES installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1)

BESS Installed Energy at BOL [kWh] (number of modules)	SMES Size [Wh]	Number of BESS modules required for 30 years ship lifetime	Total Energy charged from shore for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including energy for cooling) [GWh]	Total energy consumption for cooling [GWh]		BESS State of health at end of vessel lifetime [%]	Total Weight [ton]
					BESS	SMES		
678 x 2 (20s6p x2 = 240)	--	720	90.4005	12.9592 (14.34%)	4.2849 (4.74%)	--	87.7	17.916
	193 x2		91.9889	14.5475 (15.81%)	4.2751 (4.65%)	1.6128 (1.75%)	87.8	19.786
	417 x2		91.9640	14.5226 (15.79%)	4.2645 (4.64%)	1.6128 (1.75%)	88.1	21.969
672.35 x 2 (17s7p x2 = 238)	209 x2	714	92.0790	14.6377 (15.88%)	4.3069 (4.68%)	1.6128 (1.75%)	86.9	20.131
	400 x2		92.0510	14.6093 (15.87%)	4.2955 (4.67%)	1.6128 (1.75%)	87.0	21.976
661 x 2 (13s9p x2 = 234)	209 x2	702	92.2860	14.8450 (16.09%)	4.3808 (4.75%)	1.6128 (1.75%)	84.7	20.479
	364 x2		92.2617	14.8204 (16.06%)	4.3710 (4.74%)	1.6128 (1.75%)	84.8	21.983
644.1 x 2 (19s6p x2 = 228)	209 x2	684	92.6711	15.2298 (16.43%)	4.5184 (4.88%)	1.6128 (1.74%)	80.4	19.153
	444 x2		92.6354	15.1941 (16.40%)	4.5042 (4.86%)	1.6128 (1.74%)	80.5	21.436

For easier interpretation, in the following and in the next Paragraph 5.3, data is presented based on the total number of modules of the energy storage systems installed over a 30-year lifetime. For example, the reference study is called BESS720, which means 720 battery modules are installed over 30 years. Similarly, the configuration BESS720SC40 refers to 720 battery modules and 40 SC modules. The acronyms used to identify each electric ferry configuration are provided in **Errore. L'origine riferimento non è stata trovata.**

Table 12 and Table 13 show the inventory data used to model the life cycle of the electric ferry reference and V-ACCESS case studies according to the goal and the LCA methodological aspect defined in Paragraph 5.1 and

the data provided by the other V-ACCESS partner recapped in Paragraphs 5.2.1 and 5.2.2, Table 9 and Table 10.

Table 11 – Electric ferry case studies acronyms

Ferry case studies acronyms (BESS+SC)	BESS installed energy at the BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SC installed energy at the BoL (kWh); SC modules (unit) [Total SC modules required for 30 years ship lifetime (unit)]
Reference case: BESS720	1356 kWh; 240 [720]	-
BESS720SC40		4.52 kWh; 20 [40]
BESS720SC80		9.04 kWh; 40 [80]
BESS720SC180		13.56 kWh; 60 [180]
BESS720SC240		18.08 kWh; 80 [240]
BESS720SC300		22.6 kWh; 100 [300]
BESS684SC180	1288.2 kWh; 228 [684]	13.56 kWh; 60 [180]
BESS684SC240		18.08 kWh; 80 [240]
BESS684SC300		22.6 kWh; 100 [300]
BESS660SC160	1243 kWh; 220 [660]	18.08 kWh; 80 [240]
BESS660SC300		22.6 kWh; 100 [300]
BESS660SC360		27.3 kWh; 120 [360]
BESS630SC360	1186.5 kWh; 210 [630]	27.3 kWh; 120 [360]
BESS630SC420		31.64 kWh; 140 [420]
Ferry case studies acronyms (BESS+SSMES)	BESS installed energy at the BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SMES installed energy at the BoL (Wh)
Reference case: BESS720	1356 kWh; 240 [720]	-
BESS720SMES2		386
BESS720SMES3		834
BESS714SMES2	1344.7 kWh; 238 [714]	418
BESS714SMES3		800
BESS702SMES2	1322 kWh; 234 [702]	418
BESS702SMES3		728
BESS684SMES2	1288.2 kWh; 228 [684]	418
BESS684SMES3		888

Table 12 - Inventory data used to model the electric ferry reference (only BESS) and BESS-SC V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 9, have been modelled following the same approach).

Electric ferry case	Reference case: BESS720	BESS720 SC40	BESS684 SC180	BESS660 SC160	BESS630 SC360	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (NMC) construction phase and replacement for 30 years ship lifetime (kg)	2*17,842 0.62*17,842	2*17,842 0.54*1784 2	2*16950 0.68*16950	2*16355 0.89*16355	2*15612 1.06*15612	Own elaboration (see Paragraph 5.2.1)
SC construction phase and replacement for 30 years ship lifetime (kg)	-	2*550 2*550*0.6 4	6*550 6*550*0.35	8*550 8*550*0.91	12*550 12*550*0.33	Own elaboration (see Paragraph 5.2.2)
Energy for the mission profile (GWh)	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01	Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U
Energy losses (GWh)	8.67E+00	8.53E+00	8.63E+00	8.72E+00	8.72E+00	
Energy for cooling (BESS and SC) (GWh)	4.28E+00	4.19E+00	4.24E+00	4.28E+00	4.27E+00	

Table 13 - Inventory data used to model the electric ferry reference (only BESS) and BESS-SMES V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 10, have been modelled following the same approach).

Electric ferry case	Reference case: BESS720	BESS720 SMES2	BESS714 SMES2	BESS702 SMES2	BESS684 SMES2	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (NMC) construction phase and replacement for 30 years ship lifetime (kg)	2*17,842 0.62*17,842	2*17,842 0.61*17,842	2*17,693 0.66*17,693	2*17,395 0.77*17,395	2*16,905 0.98*16,905	Own elaboration (see Paragraph 5.2.1)
SMES construction phase and replacement for 30 years ship lifetime (unit)	-	2	2	2	2	Own elaboration (see Paragraph 5.2.2)
Energy for the mission profile (GWh)	7.74E+01	7.74E+01	7.74E+01	7.74E+01	7.74E+01	Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U
Energy losses (GWh)	8.67E+00	1.03E+01	1.03E+01	1.05E+01	1.07E+01	
Energy for cooling BESS (GWh)	4.28E+00	4.28E+00	4.31E+00	4.38E+00	4.52E+00	
Energy for cooling SMES (GWh)		1.61E+00	1.61E+00	1.61E+00	1.61E+00	

5.2.4 OSV – AHC - LCI

The OSV-AHC is a hybrid vessel featuring a power system that integrates diesel generators and a BESS as the reference case. The diesel generators serve as the primary power source, while the BESS provides

supplementary power, especially during peak demand. In hybrid ships, the BESS is charged using surplus energy from the engines and plays a crucial role in stabilizing load fluctuations, enhancing efficiency, and reducing fuel consumption.

For the purposes of the V-ACCESS project objectives, this study is specifically focused on the BESS. In the OSV-AHV reference case, the BESS unit is based on LFP lithium-ion technology (**Errore. L'origine riferimento non è stata trovata.**), with an installed energy capacity at the BoL of 1170 kWh. Over the 30-year lifespan of the ship, the BESS unit require two replacements. By the end of this period, the final battery pack retain 83.6% of its rated energy capacity.

In the V-ACCESS OSV-AHC case studies, a SC or SMES is integrated into the ship's power system to supply high peak power, thereby relieving the battery from thermal and electrical stresses that accelerate degradation, ultimately increasing the useful life of the battery. Fourteen V-ACCESS case studies are examined for the BESS-SC configuration and ten for the BESS-SMES configuration (see Table 14 and Table 15).

The installed capacities at the BoL, the replacements of the ESSs, and the energy required for the mission, including losses due to efficiency and the energy required for cooling the devices, have been calculated and provided as part of the WP1 activities. The results obtained in WP1 for the reference case and for the BESS-SC and BESS-SMES V-ACCESS case studies are recapped, respectively, in Table 14 and Table 15. The reference case is the same for both BESS-SC and BESS-SMES V-ACCESS case studies.

Table 14 – OSV - AHC case: BESS and SC installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1)

BESS Installed Energy at BOL [kWh] (number of modules)	SC Installed Energy at BOL [kWh] (number of modules)	Number of modules required for vessel lifetime		Total HESS throughput for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including energy for cooling) [GWh]	Total energy consumption for cooling [GWh]	Vessel mission total fuel consumption for vessel lifetime [Tons]	Fuel consumption associated to HESS Energy losses for vessel lifetime [Tons] (SFC = 220 g/kWh)	Fuel consumption associated to HESS cooling for vessel lifetime [Tons] (SFC = 220 g/kWh)	State of health at end of vessel lifetime [%]		Total Weight [Ton]
		BESS	SC							BESS	SC	
1170 (18s25p = 450)	--	--	--	10.2163	0.7378 (7.22%)	0.2270 (2.222%)	67310.14	162.3088	49.9332	83.66	--	23.425
	2.26 (5s2p = 10)	20	10.2133	0.7348 (7.19%)	0.2255 (2.208%)	67309.50	161.6645	49.6055	83.77	90.82	23.975	
	4.52 (5s4p = 20)	40	10.2100	0.7315 (7.16%)	0.2239 (2.193%)	67308.77	160.9409	49.2630	84.30	90.56	24.525	
	6.78 (5s6p = 30)	60	10.2063	0.7278 (7.13%)	0.2223 (2.178%)	67307.96	160.1253	48.9079	84.81	90.01	25.075	
	9.04 (5s8p = 40)	80	10.2034	0.7249 (7.10%)	0.2211 (2.167%)	67307.32	159.4875	48.6445	85.25	88.45	25.625	
	11.30 (5s10p = 50)	100	10.2001	0.7216 (7.07%)	0.2197 (2.154%)	67306.59	158.7591	48.3427	86.16	89.72	26.175	
	13.56 (5s12p = 60)	120	10.1974	0.7189 (7.05%)	0.2186 (2.144%)	67305.99	158.1535	48.1031	86.57	89.35	26.725	
	15.82 (5s14p = 70)	140	10.1946	0.7161 (7.02%)	0.2176 (2.134%)	67305.38	157.5413	47.8623	86.99	88.73	27.275	
	18.08 (5s16p = 80)	160	10.1918	0.7133 (7.00%)	0.2165 (2.124%)	67304.77	156.9319	47.6244	87.58	89.95	27.825	
1123.2 (18s24p = 432)	11.30 (5s10p = 50)	100	10.2113	0.7328 (7.18%)	0.2236 (2.189%)	67309.05	161.2145	49.1833	80.77	89.72	25.238	
	13.56 (5s12p = 60)	120	10.2081	0.7296 (7.15%)	0.2223 (2.178%)	67308.35	160.5137	48.9105	81.32	89.35	25.788	
	15.82 (5s14p = 70)	140	10.2049	0.7264 (7.12%)	0.2211 (2.166%)	67307.64	159.8051	48.6361	81.87	88.73	26.338	
	18.08 (5s16p = 80)	160	10.2016	0.7231 (7.09%)	0.2198 (2.154%)	67306.91	159.0809	48.3587	82.62	89.95	26.888	
	20.34 (5s18p = 90)	180	10.1981	0.7196 (7.06%)	0.2185 (2.142%)	67306.15	158.3158	48.0675	83.62	90.37	27.988	
1076.4 (18s23p = 414)	22.60 (5s20p = 100)	200	10.2058	0.7273 (7.13%)	0.2210 (2.166%)	67307.84	160.0105	48.6253	79.00	90.24	27.051	

Table 15 – OSV - AHC case: BESS and SMES installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1)

BESS Installed Energy at BOL [kWh] (number of modules)	SMES Size [Wh]	Number of BESS modules required for 30 years ship lifetime	Total HESS Energy throughput for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including cooling) [GWh]	BESS Energy Losses for Vessel lifetime (Including cooling) [GWh]	Total energy consumption for cooling [GWh]		Vessel mission total fuel consumption for vessel lifetime [Tons]	Fuel consumption associated to HESS total Energy loss for vessel lifetime [Tons] (SFC = 220 g/kWh)	Fuel consumption associated to HESS cooling for vessel lifetime [Tons] (SFC = 220 g/kWh)	BESS State of health at end of vessel lifetime [%]	Total Weight [ton]
						BESS	SMES					
1170 (18s25p = 450)	--	1350	10.2163	0.7378 (7.22%)	0.227 (2.22%)	--	67310.1400	162.3088	49.9332	83.66	23.425	
	209		10.7684	1.2899	0.73593	0.22637	0.55329	67431.6127	283.7788	171.5251	83.66	24.429
	425		10.7674	1.2889	0.73423	0.22581	0.55329	67431.3915	283.5577	171.4027	83.67	24.740
	630		10.7671	1.2886	0.73379	0.22566	0.55329	67431.3281	283.4942	171.397	83.68	25.028
	1060		10.7644	1.2859	0.72911	0.22414	0.55329	67430.7279	282.8941	171.0347	83.74	25.605
	2255		10.7585	1.2800	0.71893	0.22084	0.55329	67429.4422	281.6083	170.3078	84.23	27.421
1144 (20s22p = 440)	630	1320	10.7782	1.2997	0.74487	0.22948	0.55329	67433.765	285.9311	172.2082	79.13	24.106
	1060		10.7753	1.2968	0.74005	0.22790	0.55329	67433.1341	285.3002	171.8624	79.23	24.862
	2255		10.7690	1.2906	0.72945	0.22445	0.55329	67431.7571	283.9232	171.1034	79.86	26.678
1123.2 (18s24p = 432)	1060	1296	10.7691	1.2906	0.73380	0.22576	0.55329	67431.7599	283.9261	171.3897	82.14	24.67
	2255		10.7631	1.2846	0.72348	0.22240	0.55329	67430.4432	282.6093	170.6518	82.68	26.48

Regarding the LCA modelling of the ESS construction phases, the assumptions outlined for the electric ferry case study remain valid (see Paragraph 5.2.3). The operational phase was assumed to take place in Europe and was modelled using the dataset “Heavy fuel oil {RER} | market group for heavy fuel oil | Cut-off, U”, the same dataset that is present in the Ecoinvent database used as fuel in the “Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-off, U” dataset (represents the transport of one tonne of freight by a ferry over one kilometre).

The acronyms used to identify each OSV - AHC configuration are provided in Table 18.

Table 16 – OSV-AHC case studies acronyms

OSV-AHC case studies acronyms	BESS installed energy at BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SC installed energy at the BoL (kWh); SC modules (unit) [Total SC modules required for 30 years ship lifetime (unit)]
Reference case: BESS1350	1170 kWh; 450 [1350]	-
BESS1350SC20		2.26 kWh; 10 [20]
BESS1350SC40		4.52 kWh; 20 [40]
BESS1350S60		6.78 kWh; 30 [60]
BESS1350SC80		9.04 kWh; 40 [80]
BESS1350SC100		11.3 kWh; 50 [100]
BESS1350SC120		13.56 kWh; 60 [120]
BESS1350SC140		15.82 kWh; 70 [140]
BESS1350SC160		18.08 kWh; 80 [160]
BESS1296SC100		1123.2 kWh; 432 [1296]
BESS1296SC120	13.56 kWh; 60 [120]	
BESS1296SC140	15.82 kWh; 70 [140]	
BESS1296SC160	18.08 kWh; 80 [160]	
BESS1296SC180	20.34 kWh; 90 [180]	
BESS1242SC200	1076.4 kWh; 414 [1242]	22.60 kWh; 100 [200]

OSV-AHC studies acronyms (BESS+SSMES)	BESS installed energy at the BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SMES installed energy at the BoL (Wh)
Reference case: BESS1350	1170 kWh; 450 [1350]	-
BESS1350SMES1		209
BESS1350SMES1.31		425
BESS1350SMES1.6		630
BESS1350SMES2.17		1060
BESS1350SMES3.98		2255
BESS1320SMES1.6	1144 kWh; 440 [1320]	630
BESS1320SMES2.17		1060
BESS1320SMES3.98		2255
BESS1296SMES2.17	1196 kWh; 460 [1380]	1060
BESS1296SMES3.98		2255

Table 17 and Table 18 show the inventory data used to model the life cycle of the OSV-AHC reference and V-ACCESS case studies according to the goal and the LCA methodological aspect defined in Paragraph 5.1 and the data provided by the other V-ACCESS partner recapped in Paragraphs 5.2.1 and 5.2.2 and in Table 14 and Table 15.

Table 17 - Inventory data used to model the OSV-AHC reference (only BESS) and BESS-SC V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 14, have been modelled following the same approach).

OSV - AHC case	Reference case: BESS1350	BESS1350 SC20	BESS1296 SC100	BESS1242 SC200	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (LFP) construction phase and replacement for 30 years ship lifetime (kg)	2*23,400 0.82*23,400	2*23,400 0.81*23,400	2*22,464 0.96*22,464	2*21,528 1.05*21,528	Own elaboration (see Paragraph 5.2.1)
SC construction phase and replacement for 30 years ship lifetime (kg)	-	550 550*0.46	5*550 5*550*0.51	8*550 8*550*0.49	Own elaboration (see Paragraph 5.2.2)
Fuel consumption for the mission profile (ton)	2.085E+03	2.085E+03	2.085E+03	2.085E+03	Heavy fuel oil {RER} market group for heavy fuel oil Cut-off, U
Fuel consumption for the losses (ton)	1.121E+02	1.120E+02	1.120E+02	1.114E+02	
Fuel consumption for cooling (BESS and SC) (ton)	4.961E+01	4.918E+01	4.918E+01	4.863E+01	

Table 18 - Inventory data used to model the OSV - AHC reference (only BESS) and BESS-SMES V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 15, have been modelled following the same approach).

OSV - AHC case	Reference case: BESS1350	BESS1350 SMES1	BESS1320 SMES1.6	BESS1296 SMES2.17	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (LFP) construction phase and replacement for 30 years ship lifetime (kg)	2*23,400 0.82*23,400	2*23,400 0.82*23,400	2*22,880 1.04*22,880	2*22,464 0.89*22,464	Own elaboration (see Paragraph 5.2.1)
SMES construction phase and replacement for 30 years ship lifetime (unit)	-	1	1.6	2.17	Own elaboration (see Paragraph 5.2.2)
Fuel consumption for the mission profile (ton)	2.085E+03	2.085E+03	2.085E+03	2.085E+03	Heavy fuel oil {RER} market group for heavy fuel oil Cut-off, U
Fuel consumption for the losses (ton)	1.121E+02	1.219E+02	1.121E+02	1.225E+02	
Fuel consumption for cooling (BESS and SMES) (ton)	4.961E+01	1.619E+02	1,639E+02	1.614E+02	

5.2.5 Trawler - LCI

The trawler is a hybrid vessel featuring a power system that integrates diesel generators and a BESS as the reference case. Its power management strategy follows the same principles described for the OSV-AHC, where diesel generators provide the primary power supply and the BESS supports peak demand, stabilizes load fluctuations, and improves overall efficiency.

For the purposes of the V-ACCESS project objectives, this study is specifically focused on the BESS. In the trawler reference case, the BESS unit is based on LFP lithium-ion technology (Table 3 **Errore. L'origine riferimento non è stata trovata.**), with an installed energy capacity at the BoL of 273 kWh. Over the 30-year lifespan of the ship, the BESS unit require two replacements. By the end of this period, the final battery pack retain 80.46% of its rated energy capacity.

In the V-ACCESS trawler case studies, a SC or SMES is integrated into the ship's power system to supply high peak power, thereby relieving the battery from thermal and electrical stresses that accelerate degradation, ultimately increasing the useful life of the battery. Eleven V-ACCESS case studies are examined for the BESS-SC configuration and ten for the BESS-SMES configuration (see Table 19 and Table 20).

The installed capacities at the BoL, the replacements of the ESSs, and the energy required for the mission, including losses due to efficiency and the energy required for cooling the devices, have been calculated and provided as part of the WP1 activities. The results obtained in WP1 for the reference case and for the BESS-SC and BESS-SMES V-ACCESS case studies are recapped, respectively, in Table 19 and Table 20. The reference case is the same for both BESS-SC and BESS-SMES V-ACCESS case studies.

Table 19 – Trawler case: Battery energy storage system (BESS) and supercapacitor (SC) installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1).

BESS Installed Energy at BOL [kWh] (number of modules)	SC Installed Energy at BOL [kWh] (number of modules)	Number of modules required for vessel lifetime		Total HESS Energy throughput for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including energy for cooling) [GWh]	Total energy consumption for cooling [GWh]	Vessel mission total fuel consumption for vessel lifetime [Tons]	Fuel consumption associated to HESS Energy losses for vessel lifetime [Tons] (SFC = 220 g/kWh)	Fuel consumption associated to HESS cooling for vessel lifetime [Tons] (SFC = 220 g/kWh)	State of health at end of vessel lifetime [%]		Total Weight [Ton]
		BESS	SC							BESS	SC	
273 (15s7p = 105)	--	--	--	5.4803	0.38495 (7.02%)	0.1057 (1.929%)	99400.1045	92.0536	25.2865	80.46	--	5.579
	0.226 (1s1p = 1)	315	2	5.4781	0.38278 (6.99%)	0.1049 (1.916%)	99399.6254	91.5334	25.0950	82.86	91.27	5.634
	1.13 (5s1p = 5)		10	5.4771	0.38181 (6.97%)	0.1046 (1.909%)	99399.3951	91.3030	25.0038	83.36	90.79	5.854
	2.26 (5s2p = 10)		20	5.4758	0.38054 (6.95%)	0.1041 (1.901%)	99399.0897	90.9976	24.8919	83.84	89.88	6.129
	3.39 (5s3p = 15)		30	5.4733	0.37800 (6.91%)	0.1031 (1.884%)	99398.4840	90.3919	24.6530	84.79	86.45	6.404
	4.52 (5s4p = 20)		40	5.4686	0.37327 (6.83%)	0.1012 (1.850%)	99397.3518	89.2597	24.1985	86.88	89.81	6.679
	5.65 (5s5p = 25)		50	5.4654	0.37011 (6.77%)	0.1000 (1.829%)	99396.5970	88.5050	23.9101	88.11	89.63	6.954
	6.78 (5s6p = 30)		60	5.4618	0.36650 (6.71%)	0.099 (1.805%)	99395.7331	87.6410	23.5803	89.78	90.25	7.229
6.78 (5s6p = 30)	60		5.4743	0.37897 (6.92%)	0.1025 (1.873%)	99398.7144	90.6223	24.5216	79.50	86.14	6.792	
249.6 (16s6p = 96)	7.91 (5s7p = 35)	288	70	5.4707	0.37542 (6.86%)	0.1013 (1.851%)	99397.8663	89.7743	24.2204	81.16	86.24	7.067
	9.04 (5s8p = 40)		80	5.4673	0.37201 (6.80%)	0.1001 (1.831%)	99397.0507	88.9586	23.9416	82.33	85.01	7.342
	11.30 (5s10p = 50)		270	100	5.4671	0.37176 (6.80%)	0.0997 (1.824%)	99396.9921	88.9000	23.8505	78.5	85.32

Table 20 – Trawler case: Battery energy storage system (BESS) and superconducting magnet energy storage (SMES) installed energy capacity, number of modules required, energy required for the mission profile (data provided by WP1).

BESS Installed Energy at BOL [kWh] (number of modules)	SMES Size [Wh]	Number of BESS modules required for 30 years ship lifetime	Total HESS Energy throughput for vessel lifetime [GWh]	Total Energy Losses for Vessel lifetime (Including cooling) [GWh]	BESS Energy Losses for Vessel lifetime (Including cooling) [GWh]	Total energy consumption for cooling [GWh]		Vessel mission total fuel consumption for vessel lifetime [Tons]	Fuel consumption associated to HESS total Energy loss for vessel lifetime [Tons] (SFC = 220 g/kWh)	Fuel consumption associated to HESS cooling for vessel lifetime [Tons] (SFC = 220 g/kWh)	BESS State of health at end of vessel lifetime [%]	Total Weight [ton]
						BESS	SMES					
273 (15s7p = 105)	--	315	5.4803	0.38495 (7.02%)	0.1057 (1.93%)	--	99400.1045	92.0536	25.2865	80.46	5.579	
	208		6.0812	0.98585	0.37882	0.10402	0.60454	99543.7975	235.7466	169.4385	83.29	6.582
	416		6.0792	0.98393	0.37459	0.10287	0.60454	99543.3382	235.2873	169.1637	83.76	6.884
	1029		6.0784	0.98309	0.37286	0.10239	0.60454	99543.1370	235.0861	169.0490	83.81	7.777
	2028		6.0694	0.97408	0.35394	0.09716	0.60454	99540.9839	232.9330	167.7980	85.67	9.233
270.4 (13s8p = 104)	208	312	6.0828	0.98748	0.38045	0.10454	0.60454	99544.1877	236.1368	169.562	81.84	6.627
	416		6.0808	0.98550	0.37616	0.10337	0.60454	99543.7145	235.6636	169.2829	82.34	6.929
	1029		6.0800	0.98472	0.37450	0.10291	0.60454	99543.5284	235.4775	169.1729	82.76	7.823
	2028		6.0708	0.97553	0.35539	0.09762	0.60454	99541.3288	233.2779	167.9073	84.73	9.278
265.2 (17s6p = 102)	1029	306	6.0836	0.98833	0.37811	0.10405	0.60454	99544.3908	236.3399	169.4463	80.06	7.538
	2028		6.0740	0.97864	0.35850	0.09860	0.60454	99542.0738	234.0230	168.1436	82.30	8.994

Regarding the LCA modelling of the ESS construction phases, the assumptions outlined for the electric ferry case study remain valid (see Paragraph 5.2.3). The operational phase was assumed to take place in Europe and was modelled using the dataset “Heavy fuel oil {RER} | market group for heavy fuel oil | Cut-off, U.”

The acronyms used to identify each Trawler configuration are provided in Table 21.

Table 21 – Trawler case studies acronyms

Trawler case studies acronyms	BESS installed energy at BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SC installed energy at the BoL (kWh); SC modules (unit) [Total SC modules required for 30 years ship lifetime (unit)]
Reference case: BESS315	273 kWh; 105 [315]	-
BESS315SC2		0.226 kWh; 1 [2]
BESS315SC10		1.13 kWh; 5 [10]
BESS315SC20		2.26 kWh; 10 [20]
BESS315SC30		3.39 kWh; 15 [30]
BESS315SC40		4.52 kWh; 20 [40]

BESS315SC50		5.65 kWh; 25 [50]
BESS315SC60		6.78 kWh; 30 [60]
BESS288SC60	249.6 kWh; 96 [288]	6.78 kWh; 30 [60]
BESS288SC70		7.91 kWh; 35 [70]
BESS288SC80		9.04 kWh; 40 [80]
BESS270SC100	234 kWh; 90 [270]	11.30 kWh; 50 [100]
OSV-AHC studies acronyms (BESS+SSMES)	BESS installed energy at the BoL (kWh); BESS modules (unit) [Total BESS modules required for 30 years ship lifetime (unit)]	SMES installed energy at the BoL (Wh)
Reference case: BESS315	273 kWh; 105 [315]	-
BESS315SMES1		208
BESS315SMES1.31		416
BESS315SMES2.19		1029
BESS315SMES3.64		2028
BESS312SMES1	270 kWh; 104 [312]	208
BESS312SMES1.31		416
BESS312SMES2.19		1029
BESS312SMES3.64		2028
BESS306SMES2.19	265.2 kWh; 102 [306]	1029
BESS306SMES3.64		2028

Table 22 and Table 23 show the inventory data used to model the life cycle of the Trawler reference and V-ACCESS case studies according to the goal and the LCA methodological aspect defined in Paragraph 5.1 and the data provided by the other V-ACCESS partner recapped in in **Errore. L'origine riferimento non è stata trovata.** Paragraphs 5.2.1 and 5.2.2 **Errore. L'origine riferimento non è stata trovata.**, and in Table 19 and Table 20.

Table 22 - Inventory data used to model the trawler reference (only BESS) and BESS-SC V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 19, have been modelled following the same approach).

Trawler case	Reference case: BESS315	BESS315 SC2	BESS288 SC60	BESS270 SC100	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (LFP) construction phase and replacement for 30 years ship lifetime (kg)	2*5,460 0.98*5,460	2*5,460 0.857*5,460	2*4,992 1.025*4,992	2*4,680 1.075*4,680	Own elaboration (see Paragraph 5.2.1)
SC construction phase and replacement for 30 years ship lifetime (kg)	-	55 55*0.857	30*55 30*55*0.693	50*55 50*55*0.734	Own elaboration (see Paragraph 5.2.2)
Fuel consumption for the mission profile (ton)	1.218E+03	1.218E+03	1.218E+03	1.218E+03	Heavy fuel oil {RER} market group for heavy fuel oil Cut-off, U
Fuel consumption for the losses (ton)	6.678E+01	6.645E+01	6.611E+01	6.6506E+01	
Fuel consumption for cooling (BESS and SC) (ton)	2.528E+01	2.508E+01	2.451E+01	2.384E+01	

Table 23 - Inventory data used to model the trawler reference (only BESS) and BESS-SMES V-ACCESS case studies. (Only a selection of V-ACCESS cases is reported as an example; the remaining cases, as illustrated in Table 20, have been modelled following the same approach).

Trawler case	Reference case: BESS315	BESS315 SMES1	BESS312 SMES1	BESS312 SMES3.64	LCI modelling datasets (Ecoinvent & own adaptation)
BESS (LFP) construction phase and replacement for 30 years ship lifetime (kg)	2*5,460 0.98*5,460	2*5,460 0.835*5,460	2*5,408 0.908*5,408	2*5,304 0.908*5,304	Own elaboration (see Paragraph 5.2.1)
SMES construction phase and replacement for 30 years ship lifetime (unit)	-	1	1	3.64	Own elaboration (see Paragraph 5.2.2)
Fuel consumption for the mission profile (ton)	1.218E+03	1.218E+03	1.218E+03	1.218E+03	Heavy fuel oil {RER} market group for heavy fuel oil Cut-off, U
Fuel consumption for the losses (ton)	6.678E+01	6.631E+01	6.657E+01	6.689E+01	
Fuel consumption for cooling (BESS) (ton)	2.528E+01	2.488E+01	2.500E+01	2.489E+01	
Fuel consumption for cooling (SMES) (ton)	2.528E+01	1.446E+02	1.446E+02	1.446E+02	

5.3 Life Cycle Impact Assessment (LCIA) and Interpretation

In this section, the results of the environmental impact assessment of the examined hybrid power systems in the electric ferry, OSV-AHC and trawler applications are analysed and discussed. The interpretation phase encompasses all environmental impact categories, with particular emphasis on the climate change.

For easier interpretation, in the next sections, data is presented based on the total number of modules of the energy storage systems installed over a 30-year lifetime (see **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.** and Table 21).

5.3.1 Electric ferry- LCIA

Table 24 and Figure 3 summarize the results obtained for the electric ferry case, considering the reference case and the assessed V-ACCESS hybrid power energy storage systems: battery energy storage system (BESS) and Supercapacitor (SC).

Table 24: Potential life cycle environmental impacts for the reference case (BESS720) and assessed V-ACCESS Battery energy storage system – Supercapacitor (BESS-SC) case studies for the electric ferry application.

		720	720	720	720	720	720	720	684	684	684	660	660	660	630	630
BESS modules (unit)		720	720	720	720	720	720	720	684	684	684	660	660	660	630	630
SC modules (unit)		-	40	80	180	240	300	180	240	300	160	300	360	360	360	420
Impact category	Acidification [mol H+ eq]	1.67E+05	1.66E+05	1.66E+05	1.66E+05	1.66E+05	1.65E+05	1.67E+05	1.67E+05	1.66E+05	1.68E+05	1.67E+05	1.67E+05	1.68E+05	1.68E+05	1.68E+05
	Climate change [kg CO ₂ eq]	3.23E+07	3.23E+07	3.22E+07	3.22E+07	3.21E+07	3.21E+07	3.24E+07	3.23E+07	3.23E+07	3.25E+07	3.24E+07	3.23E+07	3.26E+07	3.25E+07	3.25E+07
	Particulate matter [disease inc.]	5.07E-01	5.05E-01	5.04E-01	5.05E-01	5.05E-01	5.05E-01	5.10E-01	5.09E-01	5.10E-01	5.14E-01	5.14E-01	5.13E-01	5.19E-01	5.19E-01	5.19E-01
	Eutrophication, marine [kg N eq]	2.23E+04	2.22E+04	2.22E+04	2.22E+04	2.22E+04	2.21E+04	2.24E+04	2.23E+04	2.23E+04	2.24E+04	2.24E+04	2.24E+04	2.25E+04	2.25E+04	2.25E+04
	Eutrophication, freshwater [kg P eq]	3.13E+03	3.12E+03	3.12E+03	3.11E+03	3.11E+03	3.11E+03	3.13E+03	3.12E+03	3.12E+03	3.14E+03	3.14E+03	3.13E+03	3.15E+03	3.14E+03	3.14E+03
	Eutrophication, terrestrial [mol N eq]	2.57E+05	2.57E+05	2.56E+05	2.56E+05	2.56E+05	2.55E+05	2.58E+05	2.57E+05	2.57E+05	2.59E+05	2.58E+05	2.58E+05	2.60E+05	2.59E+05	2.59E+05
	Ionising radiation [kBq U ²³⁵ eq]	6.62E+06	6.61E+06	6.59E+06	6.58E+06	6.57E+06	6.55E+06	6.62E+06	6.60E+06	6.58E+06	6.63E+06	6.61E+06	6.59E+06	6.63E+06	6.62E+06	6.62E+06
	Ozone depletion [kg CFC11 eq]	5.89E-01	5.87E-01	5.86E-01	5.85E-01	5.84E-01	5.83E-01	5.90E-01	5.88E-01	5.87E-01	5.92E-01	5.90E-01	5.89E-01	5.94E-01	5.92E-01	5.92E-01
	Photochemical ozone formation [kg NMVOC eq]	8.31E+04	8.29E+04	8.27E+04	8.26E+04	8.25E+04	8.24E+04	8.33E+04	8.30E+04	8.29E+04	8.36E+04	8.34E+04	8.32E+04	8.39E+04	8.37E+04	8.37E+04
	Resource use, minerals and metals [kg Sb eq]	2.01E+02	1.99E+02	1.98E+02	2.00E+02	2.00E+02	2.01E+02	2.06E+02	2.06E+02	2.07E+02	2.13E+02	2.13E+02	2.12E+02	2.23E+02	2.21E+02	2.21E+02

The results reveal that the hybrid energy storage configurations exhibit relatively stable environmental impacts across various categories, with some variations compared to the reference case, BESS720. Overall, most hybrid configurations show similar impacts, with slight improvements or increases in specific areas.

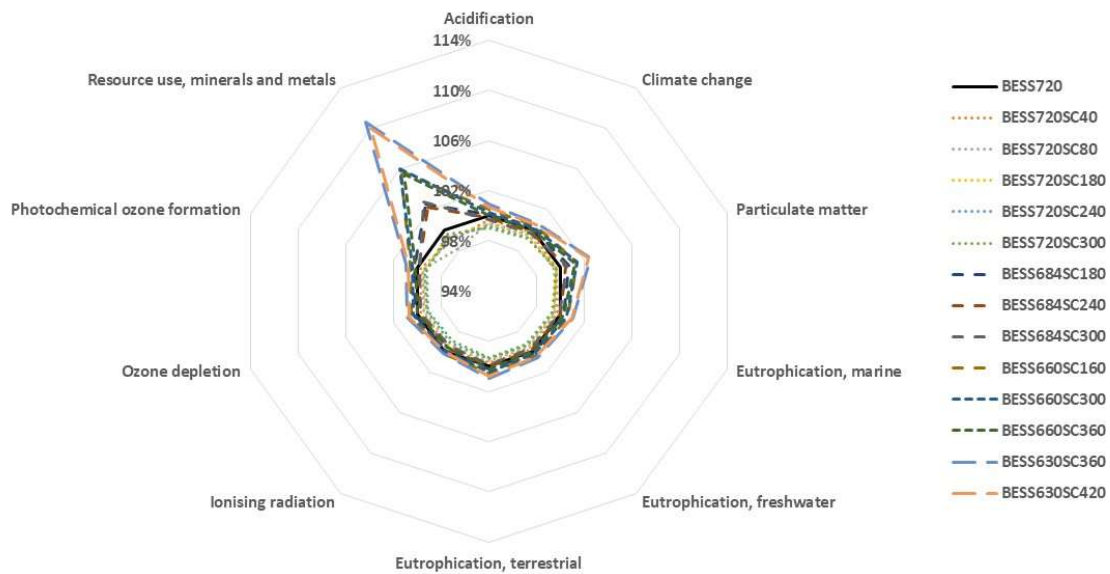


Figure 3: Graphical representation of the results obtained for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)) for the ferry case.

In terms of acidification, climate change, and eutrophication impacts, the hybrid configurations generally align closely with the reference case, with configurations like BESS720SC240 and BESS720SC300 showing slightly lower impacts in climate change (-0.68% and -0.79% respectively). However, particulate matter and resource use for minerals and metals show greater variation, with some configurations like BESS630SC360 and BESS630SC420 exhibiting higher impacts. These are the configurations with lower installed battery modules, but higher SC installed modules.

Notable differences are observed in the ionizing radiation and ozone depletion categories, with the highest values found in the BESS630 configurations. Overall, while the hybrid configurations show slight benefits in reducing some environmental impacts (especially in climate change), others like resource use and particulate matter tend to show higher values, particularly in BESS630 configurations.

The hybrid systems generally perform similarly to the reference case in most impact categories, with small improvements in climate change and particulate matter, but with trade-offs in resource use and eutrophication.

The detailed analysis of the impact category climate change (Table 25) reveals several configurations with significant reductions in CO₂eq emissions. Among these, the BESS720SC300 configuration stands out as the best option in terms of overall environmental impact. This configuration achieves the highest reduction in total CO₂eq emissions (-0.79%), with a total emission of 3.21E+07 kg CO₂ eq. The lower impact on climate change is linked to both the reduction in energy consumption during the operational phase (-0.79%) and the better SOH of the battery at the end of the 30-year vessel lifetime compared to the reference case (see Table 25).

In terms of construction phase impacts, the BESS720SC40 configuration is the best option, with a minimal increase of 0.55%, compared to the reference case. This indicates that the addition of 40 SC modules to the 720 BESS modules results in the least environmental impact during the construction phase. This is the configuration with the lowest number of SC modules added to the system. The reduction of BESS modules (reducing from 720 BESS modules to 684 and 630) and the increase of SC modules (from 180 up to 400) do not reduce the impact on the construction phase. This is because adding SC modules does not significantly increase the state of health of the batteries. The only exception is BESS684SC300 configuration that presents a significantly improve of the battery lifetime (+1.32%). It is necessary to reach a compromise on the number of supercapacitor modules to be added to the system to enhance the state of health of the batteries.

The reduction of BESS modules (720-684-630) and the increase of SC modules (180 up to 400) have a positive effect (higher reduction) on the energy losses and energy for cooling the system.

For the operational phase, both BESS720SC240 and BESS720SC300 configurations emerge as the best solutions, achieving reductions in climate change impacts of 0.90% and 1.09%, respectively. The reduction in climate change impact is directly linked to a corresponding decrease in electricity consumption of the same percentage during the operational phase, compared to the reference case. The BESS720SC240 configuration also leads in minimizing climate change impacts during the operational phase, with a total emission of 3.21E+07 kg CO₂ eq and a reduction of -0.68%. Similarly, the BESS720SC180 configuration shows notable reductions in CO₂ emissions (-0.54%) and fuel consumption (-0.71%), with improvements in battery lifetime (+4.45%). The total operational phase is consistent with variations in fuel variation.

The BESS720SC80 and BESS720SC40 configurations provide moderate reductions in CO₂ emissions (-0.45% and -0.24%) and fuel consumption (-0.49% and -0.26%), with positive impacts on battery health (+3.31% and +1.71%).

Results demonstrate the positive effects of hybridizing BESS with the addition of the SC modules in enhancing the overall environmental performance of the system.

Overall, the best configurations, present a reduction of about 1% in the climate change impacts. While this reduction might initially seem within the range of uncertainty typically associated with LCA studies, it is important to note that the primary contributor to these results is the data related to energy consumption reduction. This data is derived from primary sources and simulations, which do not have associated uncertainty. Therefore, the observed reduction in impacts is not due to uncertainty but represents real and significant results.

Table 25: Left side: life cycle impact assessment results on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)), subdivided by different process contribution, for the ferry case and percentage variation compared to the reference case. Right side: fuel reduction/increase and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

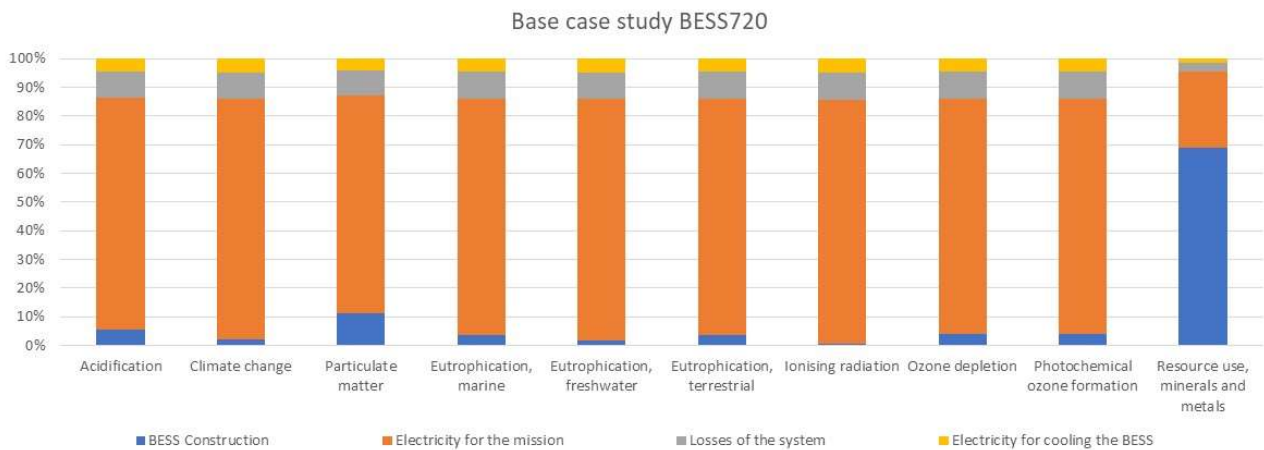
	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH (%)
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%		BESS
BESS720	6.52E+05	-	3.041E+06	-	1.502E+06	-	3.17E+07	-	3.23E+07	-	-	-
BESS720SC40	6.55E+05	0.55%	2.991E+06	-1.65%	1.470E+06	-2.12%	3.16E+07	-0.26%	3.23E+07	-0.24%	-0.26%	1.71%
BESS720SC80	6.61E+05	1.48%	2.946E+06	-3.12%	1.443E+06	-3.95%	3.15E+07	-0.49%	3.22E+07	-0.45%	-0.49%	3.31%
BESS720SC180	7.04E+05	7.95%	2.901E+06	-4.59%	1.416E+06	-5.74%	3.15E+07	-0.71%	3.22E+07	-0.54%	-0.71%	4.45%
BESS720SC240	7.17E+05	9.99%	2.863E+06	-5.83%	1.393E+06	-7.25%	3.14E+07	-0.90%	3.21E+07	-0.68%	-0.90%	5.47%
BESS720SC300	7.43E+05	13.94%	2.826E+06	-7.06%	1.371E+06	-8.74%	3.13E+07	-1.09%	3.21E+07	-0.79%	-1.09%	6.84%
BESS684SC180	7.29E+05	11.84%	3.026E+06	-0.49%	1.485E+06	-1.10%	3.17E+07	-0.10%	3.24E+07	0.14%	-0.10%	-1.37%
BESS684SC240	7.37E+05	13.02%	2.961E+06	-2.64%	1.446E+06	-3.70%	3.16E+07	-0.43%	3.23E+07	-0.16%	-0.43%	-0.46%
BESS684SC300	7.71E+05	18.31%	2.913E+06	-4.19%	1.419E+06	-5.55%	3.15E+07	-0.66%	3.23E+07	-0.28%	-0.66%	1.32%
BESS660SC160	7.64E+05	17.22%	3.058E+06	0.57%	1.500E+06	-0.11%	3.17E+07	0.05%	3.25E+07	0.40%	0.05%	-6.27%
BESS660SC300	8.00E+05	22.78%	2.999E+06	-1.37%	1.466E+06	-2.41%	3.16E+07	-0.25%	3.24E+07	0.22%	-0.25%	-3.88%
BESS660SC360	8.10E+05	24.23%	2.944E+06	-3.18%	1.434E+06	-4.54%	3.15E+07	-0.52%	3.23E+07	-0.02%	-0.52%	-2.28%
BESS630SC360	8.57E+05	31.45%	3.057E+06	0.52%	1.496E+06	-0.39%	3.17E+07	0.03%	3.26E+07	0.66%	0.03%	-10.15%
BESS630SC420	8.68E+05	33.16%	3.019E+06	-0.73%	1.474E+06	-1.90%	3.16E+07	-0.16%	3.25E+07	0.51%	-0.16%	-8.21%

Figure 4 presents the life cycle impact assessment with processes contribution considering the reference case (BESS720) and the best case of climate change reduction (BESS720SC300, reduction of $\approx 1\%$ impacts).

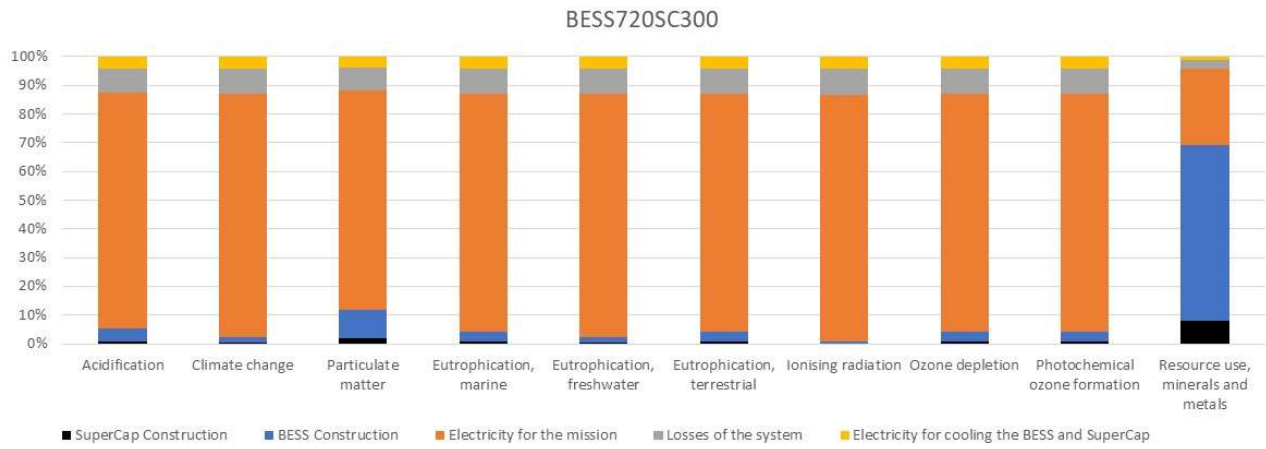
The environmental impacts across various categories are primarily driven by the electricity used for the mission, followed by the construction of the BESS and SC, which significantly affect particulate matter and resource use for minerals and metals. System losses and cooling electricity also contribute smaller but notable portions to the overall impacts. In terms of specific impact categories, mission electricity consistently emerges as the dominant contributor, making up over 80% in categories like acidification, climate change, eutrophication, ionizing radiation, ozone depletion, and photochemical ozone formation. The contribution from BESS construction is substantial in resource use and particulate matter, while the SC construction impacts eutrophication and particulate matter, particularly in the BESS720SC300 configuration.

For example, in acidification, climate change, and particulate matter, mission electricity remains the main contributor in both the base case and the BESS720SC300 configuration. However, the latter shows slightly different distribution patterns, with BESS720SC300 exhibiting lower contributions from BESS construction and slightly higher contributions from SC construction in resource use and particulate matter. Similarly, for eutrophication, ionizing radiation, and ozone depletion, both configurations have similar contributions, though BESS720SC300 tends to show slightly lower BESS construction impacts and slightly higher SC construction impacts. This variation highlights the differences in how BESS and SC construction and their respective cooling needs influence the overall environmental footprint.

Overall, the addition of SCs in the BESS720SC300 configuration results in slight variations in the contributions from different sources, with some categories showing lower impacts from BESS construction and higher impacts from SC construction. The electricity for the mission remains the dominant contributor across most impact categories.



(a)



(b)

Figure 4: Life cycle impact assessment results with processes contribution: (a) Base case study, battery storage system with 720 installed modules for 30 years lifetime (BESS720) and (b) configuration with 720 installed battery modules and 300 SC installed modules (BESS720SC300).

Table 26 and Figure 5 summarize the results obtained for the ferry case, considering the assessed hybrid storage systems: BESS and SMES.

Table 26: Potential life cycle environmental impacts for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the ferry case.

		BESS modules (unit)	720	720	720	714	714	702	702	684	684
		SMES modules (unit)	-	2	3	2	3	2	3	2	3
Impact category	Acidification [mol H+ eq]		1.67E+05	1.70E+05	1.71E+05	1.71E+05	1.71E+05	1.71E+05	1.72E+05	1.72E+05	1.73E+05
	Climate change [kg CO ₂ eq]		3.23E+07	3.29E+07	3.29E+07	3.30E+07	3.30E+07	3.31E+07	3.31E+07	3.32E+07	3.32E+07
	Particulate matter [disease inc.]		5.07E-01	5.16E-01	5.17E-01	5.17E-01	5.18E-01	5.20E-01	5.21E-01	5.25E-01	5.25E-01
	Eutrophication, marine [kg N eq]		2.23E+04	2.27E+04	2.27E+04	2.27E+04	2.27E+04	2.28E+04	2.28E+04	2.29E+04	2.29E+04
	Eutrophication, freshwater [kg P eq]		3.13E+03	3.19E+03	3.19E+03	3.19E+03	3.19E+03	3.20E+03	3.20E+03	3.21E+03	3.21E+03
	Eutrophication, terrestrial [mol N eq]		2.57E+05	2.62E+05	2.62E+05	2.62E+05	2.62E+05	2.63E+05	2.63E+05	2.65E+05	2.65E+05
	Ionising radiation [kBq U-235 eq]		6.62E+06	6.74E+06	6.74E+06	6.75E+06	6.75E+06	6.76E+06	6.76E+06	6.79E+06	6.79E+06
	Ozone depletion [kg CFC11 eq]		5.89E-01	6.01E-01	6.01E-01	6.01E-01	6.02E-01	6.03E-01	6.04E-01	6.07E-01	6.08E-01
	Photochemical ozone formation [kg NMVOC eq]		8.31E+04	8.46E+04	8.47E+04	8.47E+04	8.48E+04	8.50E+04	8.50E+04	8.55E+04	8.55E+04
	Resource use, minerals and metals [kg Sb eq]		2.01E+02	2.05E+02	2.06E+02	2.06E+02	2.07E+02	2.10E+02	2.11E+02	2.17E+02	2.18E+02

The reference configuration, BESS720, which includes 720 battery modules, generally shows the lowest environmental impacts across all categories. As additional SMES modules are introduced, the environmental impacts tend to increase. For example, the configuration BESS684SMES3, which includes 684 battery modules and 3 SMES modules, consistently shows the highest environmental impacts. This indicates that while adding SMES modules can enhance the system's performance, it also leads to higher environmental burdens, which offset the improvements achieved through the enhancement of battery performance.

This is confirmed in Figure 5 that provides a visual summary of the environmental impacts for the different configurations of hybrid energy storage systems. The graph highlights the incremental increase in impacts as more SMES modules are added to the system. This visual representation helps to quickly identify which configurations have the most significant environmental impacts, reinforcing the need to find a balance between performance enhancement and environmental sustainability.

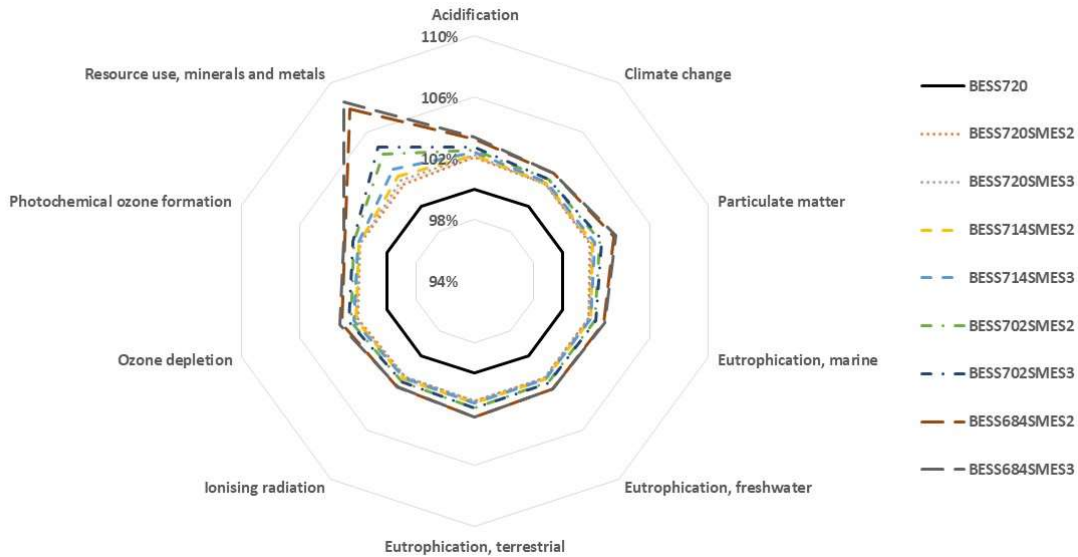


Figure 5: Graphical representation of the results obtained for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the ferry case.

Table 27 details the life cycle impact assessment on climate change for the different configurations of HESSs. It breaks down the contributions from construction and operational phases, providing a comprehensive view of the total climate change impact. The reference case, BESS720, has a total impact of 3.23E+07 kg CO₂ eq. Configurations like BESS720SMES2 show the smallest increase in climate impact at 1.82%, primarily due to relatively lower construction emissions and lower operational phase (the electricity for cooling the system with SMES represents 6% of the operational phase).

Table 27: Left side: life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)), subdivided by different process contribution, for the ferry case and percentage variation compared to the reference case. Right side: fuel reduction/increase and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

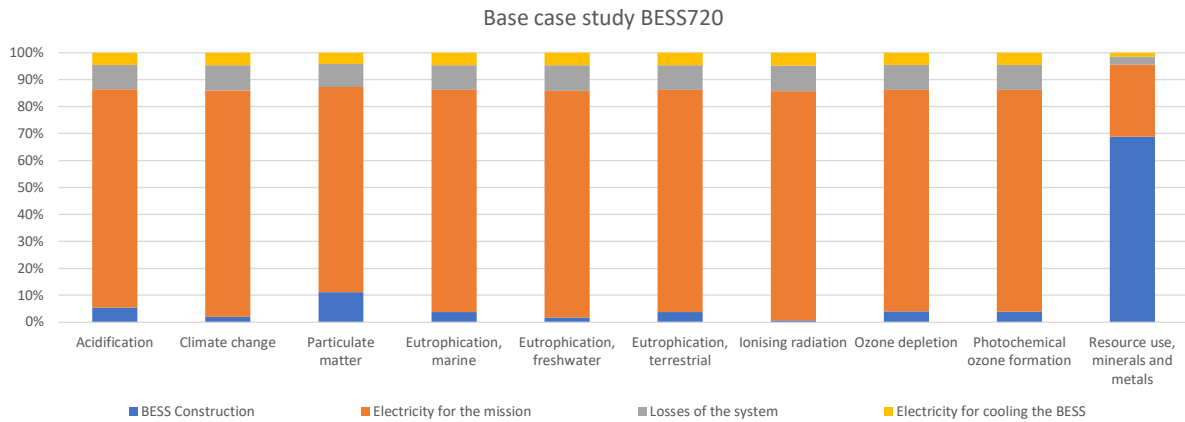
	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH (%)
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%		BESS
BESS720	6.52E+05	-	3.041E+06	-	1.502E+06	-	3.17E+07	-	3.23E+07	-	-	-
BESS720SMES2	6.83E+05	4.73%	3.036E+06	-0.17%	2.064E+06	37.41%	3.22E+07	1.76%	3.29E+07	1.82%	1.76%	0.11%
BESS720SMES3	6.95E+05	6.61%	3.031E+06	-0.33%	2.060E+06	37.16%	3.22E+07	1.73%	3.29E+07	1.83%	1.73%	0.46%
BESS714SMES2	6.88E+05	5.60%	3.056E+06	0.50%	2.075E+06	38.15%	3.23E+07	1.86%	3.30E+07	1.93%	1.86%	-0.91%
BESS714SMES3	7.03E+05	7.87%	3.050E+06	0.31%	2.071E+06	37.89%	3.23E+07	1.83%	3.30E+07	1.95%	1.83%	-0.80%
BESS702SMES2	7.04E+05	8.01%	3.103E+06	2.04%	2.101E+06	39.88%	3.24E+07	2.09%	3.31E+07	2.21%	2.09%	-3.42%
BESS702SMES3	7.19E+05	10.28%	3.098E+06	1.87%	2.098E+06	39.65%	3.23E+07	2.06%	3.31E+07	2.22%	2.06%	-3.31%
BESS684SMES2	7.38E+05	13.18%	3.190E+06	4.89%	2.149E+06	43.09%	3.25E+07	2.51%	3.32E+07	2.73%	2.51%	-8.32%
BESS684SMES3	7.52E+05	15.46%	3.182E+06	4.64%	2.144E+06	42.76%	3.25E+07	2.47%	3.32E+07	2.73%	2.47%	-8.21%

The environmental impacts associated with the construction phase vary across the different system configurations. For instance, the BESS720SMES2 configuration, which includes 720 battery modules and 2 SMES modules, shows a 4.73% increase in construction phase impacts compared to the reference case. This indicates that the addition of SMES modules does contribute to higher construction emissions, but the increase is relatively moderate. One of the key findings is the improvement in the state of health of the batteries with the addition of SMES modules. The BESS720SMES3 configuration shows a 0.46% improvement in the state of health of the batteries, which is the highest among the assessed configurations. This suggests that while the environmental impacts increase with the addition of SMES modules, there is a corresponding benefit in terms of battery health. Increasing the number of SMES modules, even while reducing the number of battery modules, improves the state of health of the batteries. The BESS720SMES3 configuration emerges as the most favourable option, balancing the trade-offs between environmental impacts and battery health. In detail, in this configuration the impact on climate change associated to BESS construction phase decreases by approximately 1%; however, the integration of the SMES increases the construction phase impacts by 7% compared to the base case. Moreover, the impacts related to energy losses due to the efficiency of the BESS and to the energy required for its cooling are reduced by 0.3% and 0.5%, respectively. These benefits, however, are offset by the additional impact associated with the energy demand for cooling the SMES. In this application, such negative effects could potentially be mitigated through the adoption of alternative SMES cooling methods.

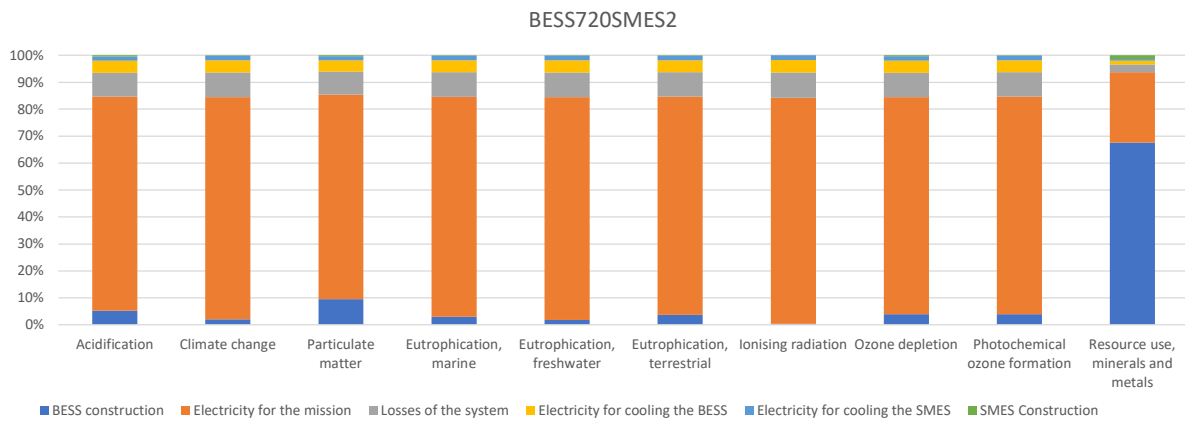
The total climate change impact for the reference case, BESS720, is 3.23E+07 kg CO₂ eq. Configurations like BESS720SMES2 and BESS720SMES3 show increases of approximately 1.8% each. These increases are relatively small, indicating that the addition of SMES modules does not drastically affect the overall climate change impact.

Considering BESS720SMES2 configuration as the best solution, Figure 6 shows the life cycle impact assessment with processes contribution for the base case (BESS720) and the best-case configuration (BESS720SMES2). Data indicates that electricity for the mission is the primary contributor to most environmental impacts, particularly in categories like climate change, ionizing radiation, and eutrophication. BESS construction has a significant impact on resource use, minerals, and metals. Losses of the system and electricity for cooling also contribute notably across various categories. SMES construction has minimal impact across all categories.

This analysis highlights the importance of optimizing electricity usage and system efficiency to reduce the overall environmental impact of the hybrid energy storage systems.



(a)



(b)

Figure 6: Life cycle impact assessment with processes contribution: (a) Base case study battery storage system with 720 installed modules for 30 years lifetime (BESS720) and (b) configuration with 720 installed battery modules and 2 Superconducting Magnetic Energy Storage (SMES) installed modules (BESS720SMES2).

5.3.2 OSV – AHC - LCIA

Table 28 and Figure 7 summarize the potential environmental impacts obtained for the OSV – AHC case, considering the assessed hybrid storage systems: batteries (BESS) and Supercapacitors (SC).

For the OSV - AHC case, the total HESS energy throughput over the vessel's lifetime was considered, rather than the vessel's total fuel consumption over its lifetime. This is because, in this case, the BESS and SC are used solely for spinning reserve, peak shaving, and/or strategic loading. Therefore, the fuel consumption required for “moving” the vessel is not considered. In other words, only the energy needed for dynamic positioning operations is considered.

The results in Table 28 indicate that the hybrid energy storage configurations exhibit relatively stable environmental impacts across various categories, with some variations compared to the reference case, BESS1350. Overall, most hybrid configurations show similar impacts, with slight improvements or increases

in specific environmental categories. In terms of acidification, climate change, and eutrophication impacts, the hybrid configurations generally align closely with the reference case. However, particulate matter and resource use, minerals and metals show greater variation, with some configurations like BESS1296SC160 and BESS1296SC180 exhibiting higher impacts. These are the configurations with lower installed battery modules, but higher SC installed modules.

Table 28: Potential life cycle environmental impacts for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)) for the OSV - AHC case.

		BESS modules (unit)										SC modules (unit)					
		1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1296	1296	1296	1296	1296	1242
		-	20	40	60	80	100	120	140	160	100	120	140	160	180	200	
Impact Category	Acidification [mol H+ eq]	1.58E+04	1.58E+04	1.58E+04	1.58E+04	1.58E+04	1.57E+04	1.57E+04	1.57E+04	1.56E+04	1.62E+04	1.62E+04	1.62E+04	1.61E+04	1.60E+04	1.64E+04	
	Climate change [kg CO ₂ eq]	2.27E+06	2.28E+06	2.28E+06	2.28E+06	2.29E+06	2.29E+06	2.29E+06	2.30E+06	2.30E+06	2.33E+06	2.33E+06	2.33E+06	2.33E+06	2.33E+06	2.37E+06	
	Particulate matter [disease inc.]	1.12E-01	1.13E-01	1.13E-01	1.13E-01	1.13E-01	1.12E-01	1.12E-01	1.12E-01	1.12E-01	1.16E-01	1.16E-01	1.16E-01	1.16E-01	1.15E-01	1.18E-01	
	Eutrophication, marine [kg N eq]	2.48E+03	2.49E+03	2.49E+03	2.50E+03	2.50E+03	2.49E+03	2.50E+03	2.51E+03	2.50E+03	2.55E+03	2.55E+03	2.56E+03	2.55E+03	2.54E+03	2.59E+03	
	Eutrophication, freshwater [kg P eq]	7.69E+01	7.76E+01	7.79E+01	7.83E+01	7.88E+01	7.86E+01	7.91E+01	7.96E+01	7.96E+01	8.20E+01	8.24E+01	8.28E+01	8.27E+01	8.24E+01	8.56E+01	
	Eutrophication, terrestrial [mol N eq]	3.31E+04	3.31E+04	3.31E+04	3.30E+04	3.30E+04	3.28E+04	3.27E+04	3.27E+04	3.26E+04	3.39E+04	3.38E+04	3.37E+04	3.36E+04	3.33E+04	3.42E+04	
	Ionising radiation [kBq U-235 eq]	3.74E+04	3.77E+04	3.79E+04	3.81E+04	3.84E+04	3.84E+04	3.86E+04	3.89E+04	3.90E+04	3.94E+04	3.96E+04	3.98E+04	3.98E+04	3.98E+04	4.08E+04	
	Ozone depletion [kg CFC11 eq]	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.89E-01	1.90E-01	1.90E-01	1.90E-01	1.90E-01	1.91E-01	
	Photochemical ozone formation [kg NMVOC eq]	1.92E+04	1.93E+04	1.93E+04	1.93E+04	1.93E+04	1.92E+04	1.92E+04	1.93E+04	1.92E+04	1.94E+04	1.94E+04	1.94E+04	1.94E+04	1.94E+04	1.96E+04	
	Resource use, minerals and metals [kg Sb eq]	1.23E+02	1.23E+02	1.23E+02	1.23E+02	1.23E+02	1.22E+02	1.22E+02	1.23E+02	1.22E+02	1.29E+02	1.29E+02	1.29E+02	1.28E+02	1.26E+02	1.32E+02	

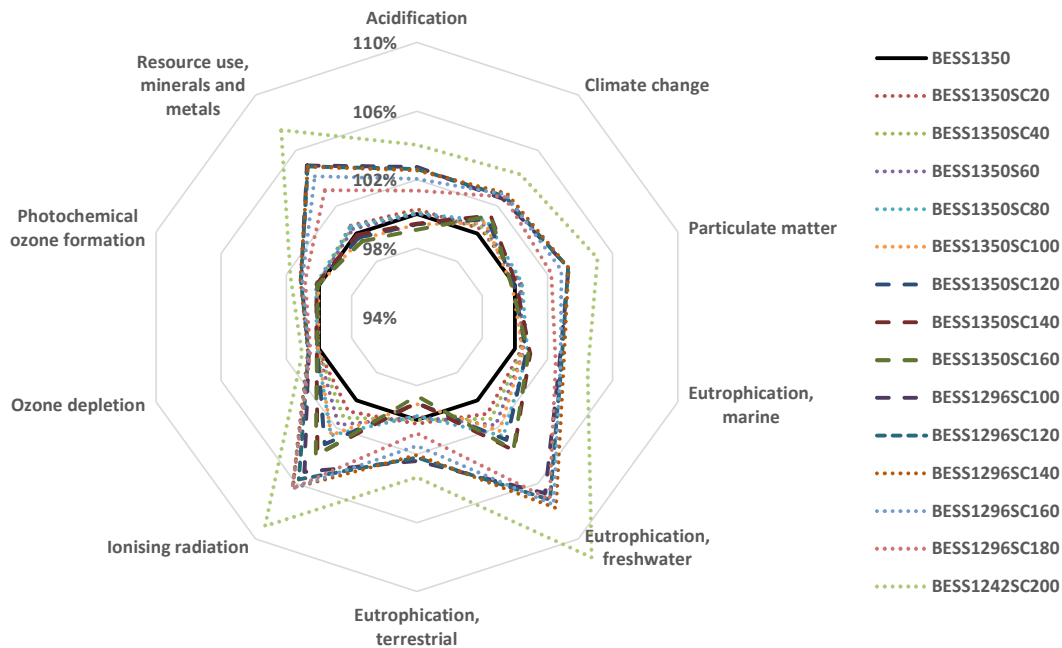


Figure 7: Graphical representation of the results obtained for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)) for the OSV case.

Table 29 provides a detailed life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (BESSs and SCs) for the OSV – AHC case, subdivided by different process contributions and percentage variation compared to the reference case. The right side of the table also includes fuel reduction and state of health at the end of the vessel's lifetime in percentage variation compared to the reference case.

Table 29: Left side: life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)), subdivided by different process contribution, for the OSV case and percentage variation compared to the reference case. Right side: fuel reduction and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	%	BESS
BESS1350	6.97E+05	-	7.86E+04	-	3.49E+04	-	1.57E+06	-	2.27E+06	-	-	-
BESS1350SC20	7.05E+05	1.23%	7.83E+04	-0.35%	3.47E+04	-0.66%	1.57E+06	-0.03%	2.28E+06	0.35%	-0.03%	0.13%
BESS1350SC40	7.09E+05	1.73%	7.80E+04	-0.68%	3.45E+04	-1.37%	1.57E+06	-0.06%	2.28E+06	0.49%	-0.06%	0.77%
BESS1350SC60	7.13E+05	2.34%	7.78E+04	-1.02%	3.42E+04	-2.08%	1.57E+06	-0.10%	2.28E+06	0.65%	-0.10%	1.37%
BESS1350SC80	7.20E+05	3.33%	7.75E+04	-1.43%	3.40E+04	-2.60%	1.57E+06	-0.13%	2.29E+06	0.93%	-0.13%	1.90%
BESS1350SC100	7.17E+05	2.94%	7.72E+04	-1.80%	3.38E+04	-3.21%	1.57E+06	-0.16%	2.29E+06	0.79%	-0.16%	2.99%
BESS1350SC120	7.23E+05	3.80%	7.70E+04	-2.02%	3.36E+04	-3.69%	1.57E+06	-0.18%	2.29E+06	1.04%	-0.18%	3.48%
BESS1350SC140	7.30E+05	4.76%	7.67E+04	-2.45%	3.35E+04	-4.16%	1.57E+06	-0.21%	2.30E+06	1.31%	-0.21%	3.98%
BESS1350SC160	7.30E+05	4.76%	7.65E+04	-2.67%	3.33E+04	-4.64%	1.57E+06	-0.24%	2.30E+06	1.30%	-0.24%	4.69%
BESS1296SC100	7.54E+05	8.30%	7.84E+04	-0.19%	3.44E+04	-1.53%	1.57E+06	-0.04%	2.33E+06	2.52%	-0.05%	-3.45%
BESS1296SC120	7.59E+05	8.95%	7.81E+04	-0.60%	3.42E+04	-2.06%	1.57E+06	-0.08%	2.33E+06	2.69%	-0.08%	-2.80%
BESS1296SC140	7.64E+05	9.72%	7.78E+04	-0.99%	3.40E+04	-2.63%	1.57E+06	-0.11%	2.33E+06	2.91%	-0.11%	-2.14%
BESS1296SC160	7.63E+05	9.49%	7.75E+04	-1.38%	3.38E+04	-3.20%	1.57E+06	-0.14%	2.33E+06	2.82%	-0.14%	-1.24%
BESS1296SC180	7.60E+05	9.06%	7.72E+04	-1.78%	3.36E+04	-3.77%	1.57E+06	-0.17%	2.33E+06	2.66%	-0.18%	-0.05%
BESS1242SC200	7.60E+05	9.06%	7.80E+04	-0.78%	3.40E+04	-2.62%	1.57E+06	-0.10%	2.33E+06	2.71%	-0.10%	-5.57%

The detailed analysis of the impact category climate change reveals configurations like BESS1350SC20 and BESS1350SC40 showing the lowest increases of 0.35% and 0.49%, respectively. These increases are relatively small, indicating that the addition of SC modules does not drastically affect the overall climate change impact. This result is also confirmed in the case of configurations with a higher number of SC modules, such as BESS1350SC160, that shows a negligible impact increase in total climate change (1.30%), but also the highest reduction in the impact related to fuel consumption for the operational phase (-0.24%).

In terms of construction phase impacts, the BESS1350SC20 configuration shows a minimal increase of 1.23% compared to the reference case, BESS1350. This indicates that the addition of 20 SC modules to the 1350 BESS modules results in a negligible increase in the environmental impact during the construction phase.

One of the key findings is the improvement in the state of health of the batteries with the addition of SC modules. The BESS1350SC160 configuration shows a 4.69% improvement in the state of health of the batteries, which is the highest among the assessed configurations. This suggests that while the environmental impacts increase with the addition of SC modules, there is a corresponding benefit in terms of battery health, which helps to reduce the impacts associated with battery manufacturing.

Increasing the number of SC modules improves the state of health of the batteries. However, this comes at the cost of higher construction impacts. The BESS1350SC160 configuration emerges as the most favourable option, balancing the trade-offs between environmental impacts increase associated to a larger SC and the lower ones associate to a higher battery state of health. Identifying this trade-off point is crucial for optimizing the design of hybrid energy storage systems to achieve both environmental sustainability and enhanced battery performance.

For the operational phase, both BESS1350SC160 and BESS1350SC140 configurations emerge as the best solutions, with reductions of 0.24% and 0.21%, respectively. This is primarily due to the reductions in fuel consumption and improvements in battery health (+4.69% and +3.98%), observed in these configurations.

The BESS1350SC120 configuration also leads in minimizing climate change impacts during the operational phase, with a total emission of 2.29E+06 kg CO₂ eq and a reduction of -0.18%. Similarly, the BESS1350SC100 configuration shows reductions in CO₂ emissions and fuel consumption (-0.16%), with improvements in battery health (+2.99%).

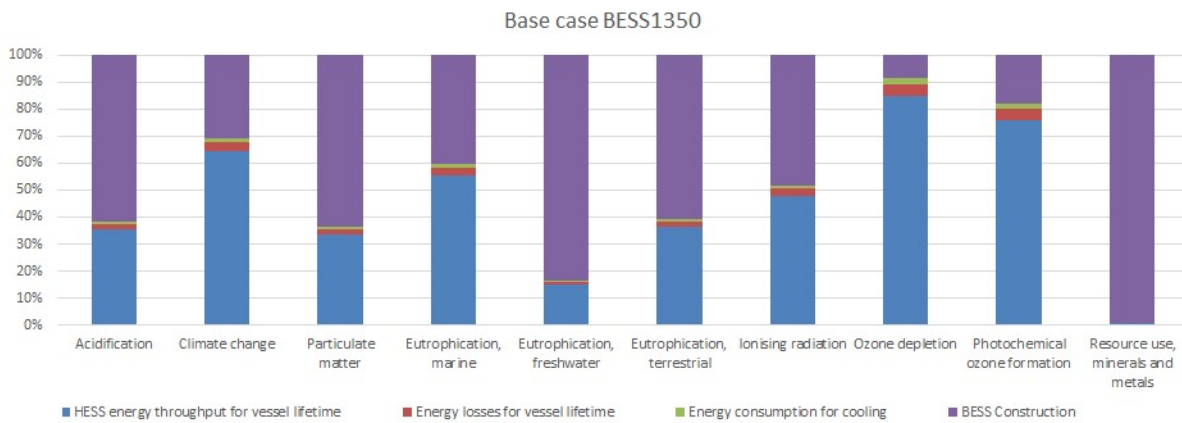
The operational phase impacts are primarily driven by the electricity required for the mission. Configurations with additional SC modules, such as BESS1350SC160, show a decrease in operational phase impacts, with a reduction of 0.24%. This decrease is due to the higher efficiency and reduced fuel consumption in the operational phase.

Considering BESS1350SC20 configuration as the best solution in terms of lower increase in total climate change impact and BESS1350SC160 the best solution in terms of higher reduction of impacts in the operational phase, Figure 8 shows the life cycle impact assessment with processes contribution for the base case (BESS720) and these best-case configurations.

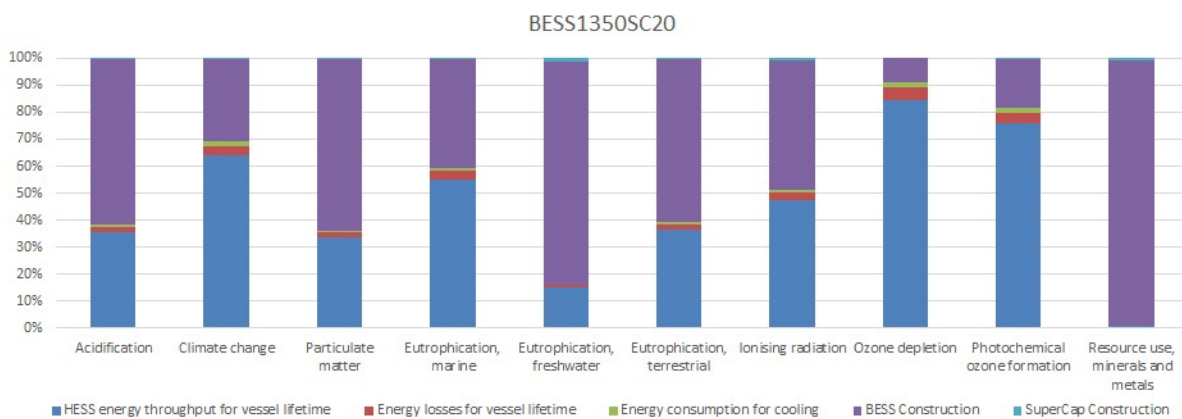
The environmental impacts across various categories are primarily driven by the electricity used for the mission, followed by the construction of the BESS and SC, which significantly affect particulate matter,

eutrophication and resource use minerals and metals. System losses and cooling electricity also contribute smaller but notable portions to the overall impacts.

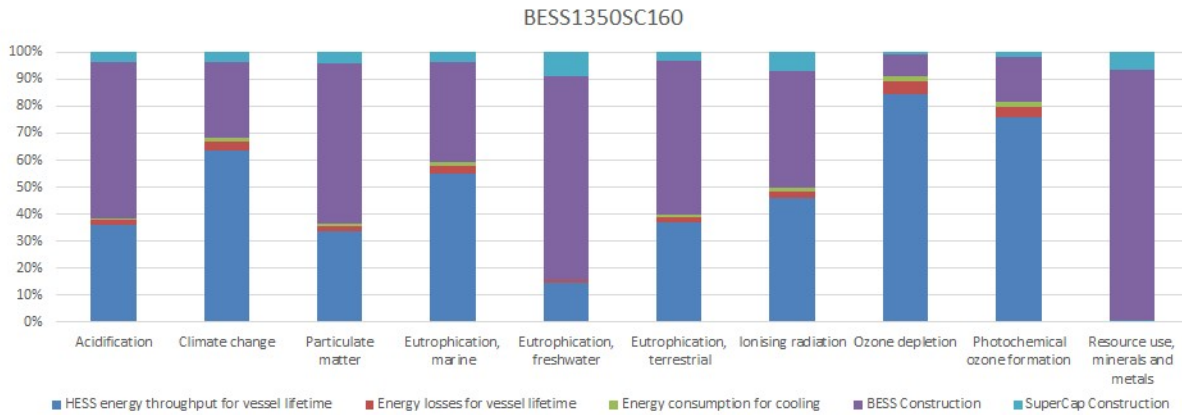
In acidification, climate change, and particulate matter impact categories, mission electricity remains the main contributor in both the base case and the BESS1350SC160 configuration. However, the latter shows slightly different distribution patterns, with BESS1350SC160 exhibiting lower contributions from BESS construction and slightly higher contributions from SC construction in resource use and particulate matter. Similarly, for eutrophication, ionizing radiation, and ozone depletion, both configurations have similar contributions, though BESS1350SC160 tends to show slightly lower BESS construction impacts and slightly higher SC construction impacts. This variation highlights the differences in how BESS and SC construction and their respective cooling needs influence the overall environmental footprint.



(a)



(b)



(c)

Figure 8: Life cycle impact assessment with processes contribution: (a) Base case study battery storage system with 1350 installed modules for 30 years lifetime (BESS1350), (b) best configuration in terms of higher CO₂ reduction and lower contribution of the Construction phase - configuration with 1350 installed battery modules and 20 SC installed modules (BESS1350SC20), and (c) best configuration in terms of higher operational phase reduction - configuration with 1350 installed battery modules and 1600 SC installed modules (BESS1350SC160) .

Table 30 and Figure 9 summarize the results obtained for the OSV – AHC case, considering the assessed hybrid storage systems: BESS and SMES.

Table 30: Potential environmental impacts for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the OSV case.

		BESS modules (unit)	1350	1350	1350	1350	1350	1350	1320	1320	1320	1296	1296
		SMES modules (unit)	-	1	1.31	1.6	2.17	3.98	1	2.17	3.98	2.17	3.98
Impact category	Acidification [mol H+ eq]		1.58E+04	1.65E+04	1.66E+04	1.67E+04	1.69E+04	1.74E+04	1.72E+04	1.74E+04	1.80E+04	1.67E+04	1.73E+04
	Climate change [kg CO ₂ eq]		2.27E+06	2.37E+06	2.37E+06	2.38E+06	2.39E+06	2.41E+06	2.42E+06	2.43E+06	2.45E+06	2.38E+06	2.40E+06
	Particulate matter [disease inc.]		1.12E-01	1.16E-01	1.16E-01	1.16E-01	1.17E-01	1.18E-01	1.20E-01	1.21E-01	1.22E-01	1.16E-01	1.17E-01
	Eutrophication, marine [kg N eq]		2.48E+03	2.58E+03	2.58E+03	2.59E+03	2.59E+03	2.61E+03	2.64E+03	2.65E+03	2.67E+03	2.58E+03	2.60E+03
	Eutrophication, freshwater [kg P eq]		7.69E+01	7.86E+01	7.89E+01	7.92E+01	7.97E+01	8.10E+01	8.28E+01	8.33E+01	8.45E+01	7.89E+01	8.01E+01
	Eutrophication, terrestrial [mol N eq]		3.31E+04	3.39E+04	3.40E+04	3.40E+04	3.41E+04	3.43E+04	3.52E+04	3.53E+04	3.54E+04	3.39E+04	3.40E+04
	Ionising radiation [kBq U-235 eq]		3.74E+04	3.91E+04	3.93E+04	3.95E+04	3.99E+04	4.09E+04	4.06E+04	4.09E+04	4.19E+04	3.97E+04	4.07E+04
	Ozone depletion [kg CFC11 eq]		1.89E-01	1.99E-01	2.00E-01	2.00E-01	2.00E-01	2.02E-01	2.01E-01	2.02E-01	2.03E-01	2.00E-01	2.02E-01
	Photochemical ozone formation [kg NMVOC eq]		1.92E+04	2.02E+04	2.02E+04	2.02E+04	2.02E+04	2.03E+04	2.04E+04	2.04E+04	2.05E+04	2.02E+04	2.03E+04
	Resource use, minerals and metals [kg Sb eq]		1.23E+02	1.24E+02	1.25E+02	1.25E+02	1.26E+02	1.27E+02	1.32E+02	1.32E+02	1.34E+02	1.24E+02	1.26E+02

The results show non negligible increase across various categories with the addition of SMES modules. Acidification impacts rise from 1.58E+04 mol H+ eq in the base case (BESS1350) to 1.80E+04 mol H+ eq in the BESS1350SMES3.98 configuration (+13.8%). Similarly, climate change impacts increase from 2.27E+06 kg CO₂ eq to 2.45E+06 kg CO₂ eq (+7.9%), and particulate matter impacts from 1.12E-01 to 1.22E-01 disease incidence (+8.2%).

In the other impact categories, the increase in impacts ranges from a minimum of 6.7% for photochemical ozone formation to a maximum of 10.4% for freshwater eutrophication.

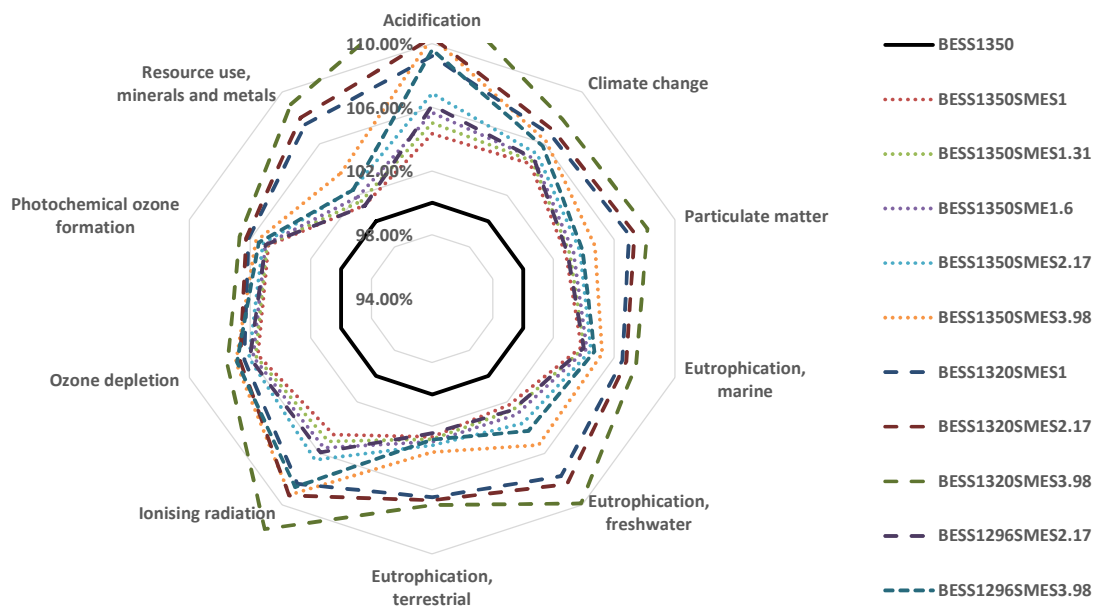


Figure 9: Graphical representation of the results obtained for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the OSV case.

Table 31 provides a detailed life cycle impact assessment on climate change (kg CO₂ eq) for the assessed hybrid energy storage systems, subdivided by different process contributions and percentage variation compared to the reference case.

The BESS1350SMES1 configuration shows a 2.30% increase in construction phase impacts compared to the reference case, BESS1350. For example, the BESS1350SMES3.98 configuration shows an 8.15% increase in construction phase impacts. Nevertheless, this configuration shows a 0.68% improvement in the state of health of the batteries, which is the highest among the assessed configurations. This suggests that while the environmental impacts increase with the addition of SMES modules, there is a corresponding benefit in terms of battery health.

As the number of SMES modules increases, energy losses also escalate. Cooling energy demand rises by more than 200% compared to the reference case, highlighting the necessity of exploring alternative cooling methods for SMES systems to reduce energy consumption during the operational phase. Furthermore,

configurations with fewer BESS modules and a higher number of SMES modules tend to perform worse, particularly in terms of battery health, which is notably degraded in the most unfavourable configurations.

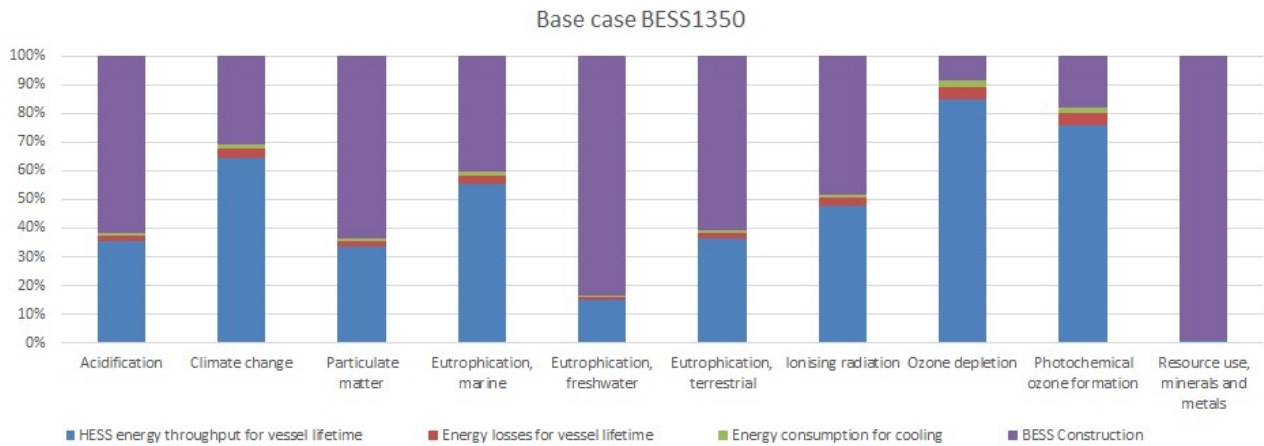
Considering BESS1350SMES1 configuration as the best solution in terms of lower increase in total climate change impact, Figure 10 shows the life cycle impact assessment with processes contribution for the base case (BESS1350) and this best-case configuration.

The environmental impacts across various categories are primarily driven by the electricity used for the mission, followed by the construction of the BESS and SMES, which significantly affect particulate matter, eutrophication and resource use minerals and metals. System losses and cooling electricity also contribute smaller but notable portions to the overall impacts.

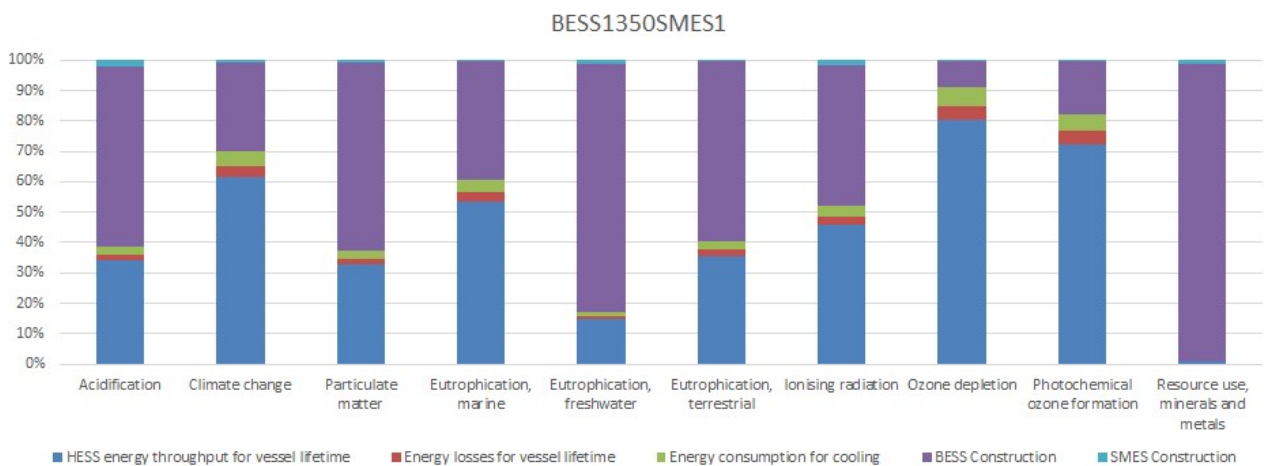
In climate change, ionizing radiation, ozone depletion and photochemical ozone formation impact categories, mission electricity remains the main contributor in both the base case and the BESS1350SMES1 configuration. However, the latter shows slightly different distribution patterns, with BESS1350SMES1 exhibiting lower contributions from BESS construction and low but visible contribution from SMES construction in resource use and particulate matter. Similarly, for eutrophication, ionizing radiation, and ozone depletion, both configurations have similar contributions, though BESS1350SMES1 tends to show slightly lower BESS construction impacts and visible the SMES construction impacts. This variation highlights the differences in how BESS and SMES construction and their respective cooling needs influence the overall environmental footprint.

Table 31: Left side: life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)), subdivided by different process contribution, for the OSV case and percentage variation compared to the reference case. Right side: fuel increase and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	%	BESS
BESS1350	6.97E+05	-	7.86E+04	-	3.49E+04	-	1.57E+06	-	2.27E+06	-	-	-
BESS1350SMES1	7.13E+05	2.30%	8.53E+04	8.49%	1.13E+05	224.19%	1.66E+06	5.41%	2.37E+06	4.45%	5.40%	0.00%
BESS1350SMES1.31	7.17E+05	3.00%	8.54E+04	8.63%	1.13E+05	223.44%	1.66E+06	5.40%	2.37E+06	4.66%	5.39%	0.01%
BESS1350SMES1.6	7.22E+05	3.65%	8.54E+04	8.66%	1.13E+05	223.25%	1.66E+06	5.39%	2.38E+06	4.86%	5.39%	0.02%
BESS1350SMES2.17	7.30E+05	4.85%	8.57E+04	9.04%	1.12E+05	221.18%	1.66E+06	5.37%	2.39E+06	5.21%	5.36%	0.10%
BESS1350SMES3.98	7.53E+05	8.15%	8.63E+04	9.88%	1.11E+05	216.70%	1.66E+06	5.31%	2.41E+06	6.18%	5.31%	0.68%
BESS1320SMES1.6	7.62E+05	9.32%	8.54E+04	8.66%	1.15E+05	228.13%	1.66E+06	5.50%	2.42E+06	6.67%	5.50%	-5.41%
BESS1320SMES2.17	7.69E+05	10.46%	8.57E+04	9.04%	1.14E+05	226.00%	1.66E+06	5.47%	2.43E+06	7.00%	5.47%	-5.30%
BESS1320SMES3.98	7.91E+05	13.53%	8.64E+04	9.90%	1.12E+05	221.33%	1.66E+06	5.41%	2.45E+06	7.91%	5.41%	-4.54%
BESS1296SMES2.17	7.22E+05	3.58%	8.57E+04	9.05%	1.13E+05	223.25%	1.66E+06	5.41%	2.38E+06	4.85%	5.41%	-1.82%
BESS1296SMES3.98	7.44E+05	6.83%	8.64E+04	9.89%	1.11E+05	218.70%	1.66E+06	5.35%	2.40E+06	5.81%	5.35%	-1.17%



(a)



(b)

Figure 10.11 Life cycle impact assessment with processes contribution: (a) Base case study battery storage system with 1350 installed modules for 30 years lifetime (BESS1350) and (b) configuration with 1350 installed battery modules and 1 Superconducting Magnetic Energy Storage (SMES) installed module (BESS1350SMES1).

5.3.3 Trawler - LCIA

Table 32 and Figure 12 summarize the potential environmental impacts obtained for the Trawler case reference case and the V-ACCESS case studies in which a hybrid power system consisting of the integration of a supercapacitor (SC) to support the battery energy storage system (BESS).

For the same reasons of the previous case, also in the trawler case, the total HESS energy throughput (Table 19) over the vessel's lifetime was considered, rather than the vessel's total fuel consumption over its lifetime. This because the energy consumption related to the hybrid power system is represented by this metric.

The results in Table 32 indicate that the hybrid power energy storage configurations exhibit relatively stable environmental impacts across various categories, with some variations compared to the reference case, BESS315. Overall, most hybrid configurations show similar impacts, with slight improvements or increases in specific areas. In terms of acidification, climate change, and eutrophication (terrestrial), ozone depletion and photochemical ozone formation impacts, the hybrid configurations generally align closely with the reference case, with configurations like BESS315SC2 and BESS315SC20 showing slightly lower impacts in climate change. However, eutrophication (freshwater), ionising radiation and resource use minerals and metals show greater variation, with some configurations like BESS270SC100 and BESS288SC80 exhibiting higher impacts. These are the configurations with lower number of installed battery modules, but higher number of SC installed modules.

Table 32: Potential environmental impacts for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)) for the Trawler case.

		BESS modules (unit)										270		
		315	315	315	315	315	315	315	315	315	288	288	288	270
		SC modules (unit)										100		
		-	2	10	20	30	40	50	60	60	70	80	100	
Impact category	Acidification [mol H+ eq]	5.93E+03	5.83E+03	5.84E+03	5.86E+03	5.86E+03	5.80E+03	5.78E+03	5.74E+03	5.98E+03	5.96E+03	5.96E+03	6.04E+03	
	Climate change [kg CO ₂ eq]	1.09E+06	1.08E+06	1.08E+06	1.09E+06	1.09E+06	1.09E+06	1.09E+06	1.09E+06	1.11E+06	1.11E+06	1.11E+06	1.13E+06	
	Particulate matter [disease inc.]	4.15E-02	4.08E-02	4.09E-02	4.11E-02	4.12E-02	4.07E-02	4.07E-02	4.04E-02	4.22E-02	4.21E-02	4.22E-02	4.29E-02	
	Eutrophication, marine [kg N eq]	1.11E+03	1.10E+03	1.10E+03	1.11E+03	1.11E+03	1.11E+03	1.11E+03	1.10E+03	1.13E+03	1.13E+03	1.14E+03	1.15E+03	
	Eutrophication, freshwater [kg P eq]	2.32E+01	2.27E+01	2.29E+01	2.32E+01	2.36E+01	2.33E+01	2.34E+01	2.34E+01	2.51E+01	2.52E+01	2.56E+01	2.66E+01	
	Eutrophication, terrestrial [mol N eq]	1.25E+04	1.23E+04	1.23E+04	1.24E+04	1.24E+04	1.22E+04	1.22E+04	1.21E+04	1.26E+04	1.25E+04	1.25E+04	1.26E+04	
	Ionising radiation [kBq U-235 eq]	1.57E+04	1.56E+04	1.57E+04	1.58E+04	1.60E+04	1.60E+04	1.60E+04	1.61E+04	1.66E+04	1.67E+04	1.69E+04	1.72E+04	
	Ozone depletion [kg CFC11 eq]	1.05E-01	1.04E-01	1.04E-01	1.05E-01	1.05E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.05E-01	1.05E-01	1.05E-01	1.05E-01
	Photochemical ozone formation [kg NMVOC eq]	1.00E+04	1.00E+04	1.00E+04	1.00E+04	1.00E+04	1.00E+04	1.00E+04	9.98E+03	1.01E+04	1.01E+04	1.01E+04	1.01E+04	
	Resource use, minerals and metals [kg Sb eq]	3.06E+01	2.95E+01	2.96E+01	2.99E+01	3.00E+01	2.93E+01	2.92E+01	2.88E+01	3.17E+01	3.15E+01	3.17E+01	3.28E+01	

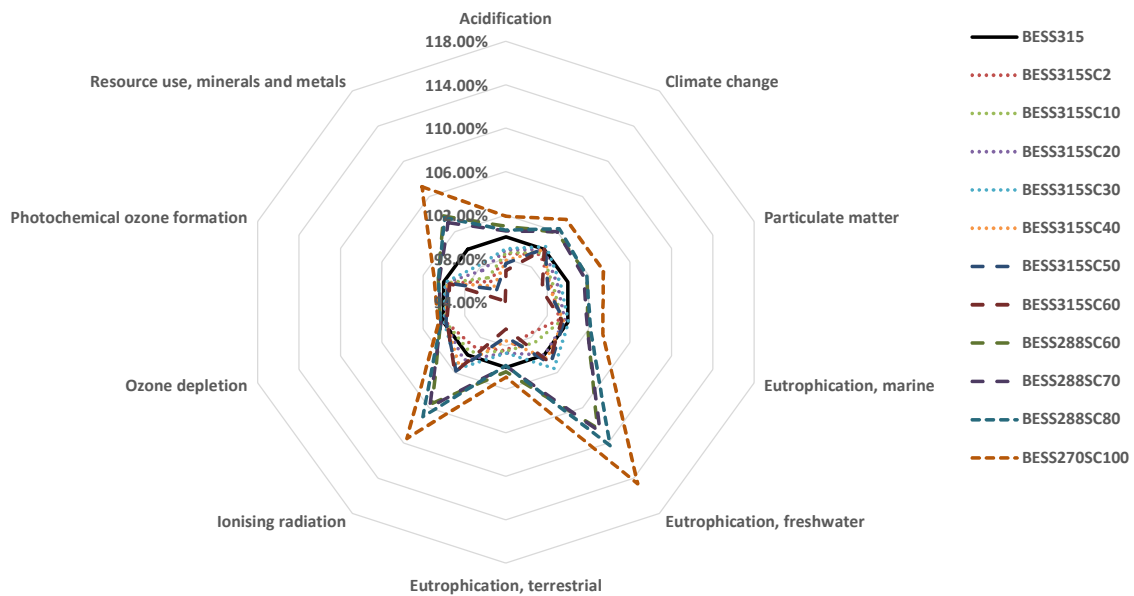


Figure 12: Graphical representation of the results obtained for the assessed hybrid energy storage systems: Battery energy storage system (BESS) and Supercapacitors (SC) for the Trawler case.

Table 33 provides a detailed life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (BESSs and SCs) for the trawler case, subdivided by different process contributions and percentage variation compared to the reference case. The right side of the table also includes fuel reduction and BESS state of health at the end of the vessel's lifetime in percentage variation compared to the reference case.

The detailed analysis of the climate change impact category reveals that hybrid configurations such as BESS315SC2 and BESS315SC10 show the highest reductions, with decreases of 0.58% and 0.36%, respectively. Configurations with a higher number of supercapacitor (SC) modules, such as BESS315SC60, display a slight increase in the total climate change impact (0.03%), despite achieving the greatest reduction in fuel consumption (-0.34%). This outcome is due to the fact that, although the addition of supercapacitors leads to lower fuel consumption and contributes to preserving the battery's state of health over the 30-year ship lifetime (reaching 11.58% in this case), the resulting environmental benefits are outweighed by the increased impact associated with the production of the supercapacitors (1.98%).

In terms of construction phase impacts, the BESS315SC2 configuration shows a decrease of 3.46% compared to the reference case, BESS315. This indicates that the addition of 2 SC modules to the 315 BESS modules enhanced the state of health of the batteries at the end of the vessel lifetime, resulting the decrease of the impact related to the construction phase. As the number of SC modules increases, the impacts associated with the construction phase also rise. While this configuration leads to an improved SoH of the BESS—thereby reducing the impacts related to its own construction—the overall benefit is not sufficient to offset the additional environmental burden introduced by the manufacturing of the supercapacitors. The BESS315SC2

configuration emerges as the most favourable option, balancing the trade-offs between higher environmental impacts associated to SC manufacturing and lower impact associated to BESS manufacturing due to a better battery state of health at the end of the ship lifetime. Identifying this trade-off point is crucial for optimizing the design of hybrid energy storage systems to achieve both environmental sustainability and enhanced battery performance.

The operational phase impacts are primarily driven by the electricity required for the mission (the same for the different configurations, 8.52E05 kgCO₂eq). The BESS315SC60 configuration emerges as the best solution, in terms of operational phase, with reduction of 0.34%. This configuration also shows significant reductions in fuel consumption and improvements in battery health (11.58%).

Table 33: Left side1. life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Supercapacitors (SC)), subdivided by different process contribution, for the Trawler case and percentage variation compared to the reference case. Right side: fuel reduction/increase and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	%	BESS
BESS315	1.72E+05	0.00%	4.67E+04	0.00%	1.77E+04	0.00%	9.17E+05	0.00%	1.09E+06	0.00%	0.00%	-
BESS315SC2	1.66E+05	-3.46%	4.65E+04	-0.49%	1.75E+04	-0.79%	9.16E+05	-0.04%	1.08E+06	-0.58%	-0.04%	2.98%
BESS315SC10	1.68E+05	-1.98%	4.64E+04	-0.73%	1.75E+04	-1.07%	9.16E+05	-0.06%	1.08E+06	-0.36%	-0.06%	3.60%
BESS315SC20	1.72E+05	0.28%	4.62E+04	-1.00%	1.74E+04	-1.54%	9.16E+05	-0.08%	1.09E+06	-0.02%	-0.08%	4.20%
BESS315SC30	1.76E+05	2.67%	4.60E+04	-1.56%	1.72E+04	-2.49%	9.16E+05	-0.13%	1.09E+06	0.31%	-0.13%	5.38%
BESS315SC40	1.74E+05	1.15%	4.55E+04	-2.58%	1.69E+04	-4.27%	9.15E+05	-0.21%	1.09E+06	0.00%	-0.21%	7.98%
BESS315SC50	1.75E+05	2.15%	4.52E+04	-3.28%	1.67E+04	-5.42%	9.14E+05	-0.27%	1.09E+06	0.11%	-0.27%	9.51%
BESS315SC60	1.75E+05	1.98%	4.47E+04	-4.21%	1.66E+04	-6.37%	9.14E+05	-0.34%	1.09E+06	0.03%	-0.34%	11.58%
BESS288SC60	1.94E+05	12.98%	4.62E+04	-1.00%	1.71E+04	-3.05%	9.16E+05	-0.11%	1.11E+06	1.96%	-0.11%	-1.19%
BESS288SC70	1.95E+05	13.70%	4.59E+04	-1.84%	1.69E+04	-4.19%	9.15E+05	-0.17%	1.11E+06	2.02%	-0.18%	0.87%
BESS288SC80	2.00E+05	16.21%	4.55E+04	-2.64%	1.67E+04	-5.30%	9.15E+05	-0.24%	1.11E+06	2.36%	-0.24%	2.32%
BESS270SC100	2.11E+05	22.80%	4.55E+04	-2.58%	1.67E+04	-5.70%	9.14E+05	-0.24%	1.13E+06	3.40%	-0.24%	-2.44%

Considering the BESS315SC2 configuration as the best solution in terms of higher decrease in total climate change impact, Figure 13 shows the life cycle impact assessment with processes contribution for the base case (BESS315) and this best-case configuration. Data indicates that the primary contributors to the total climate change impact are the operational phases followed by construction phase.

The environmental impacts across various categories are primarily driven by the electricity used for the mission, with exception of the resource use, minerals and metals impact category that is mainly (98%) driven by the construction of the BESSs.

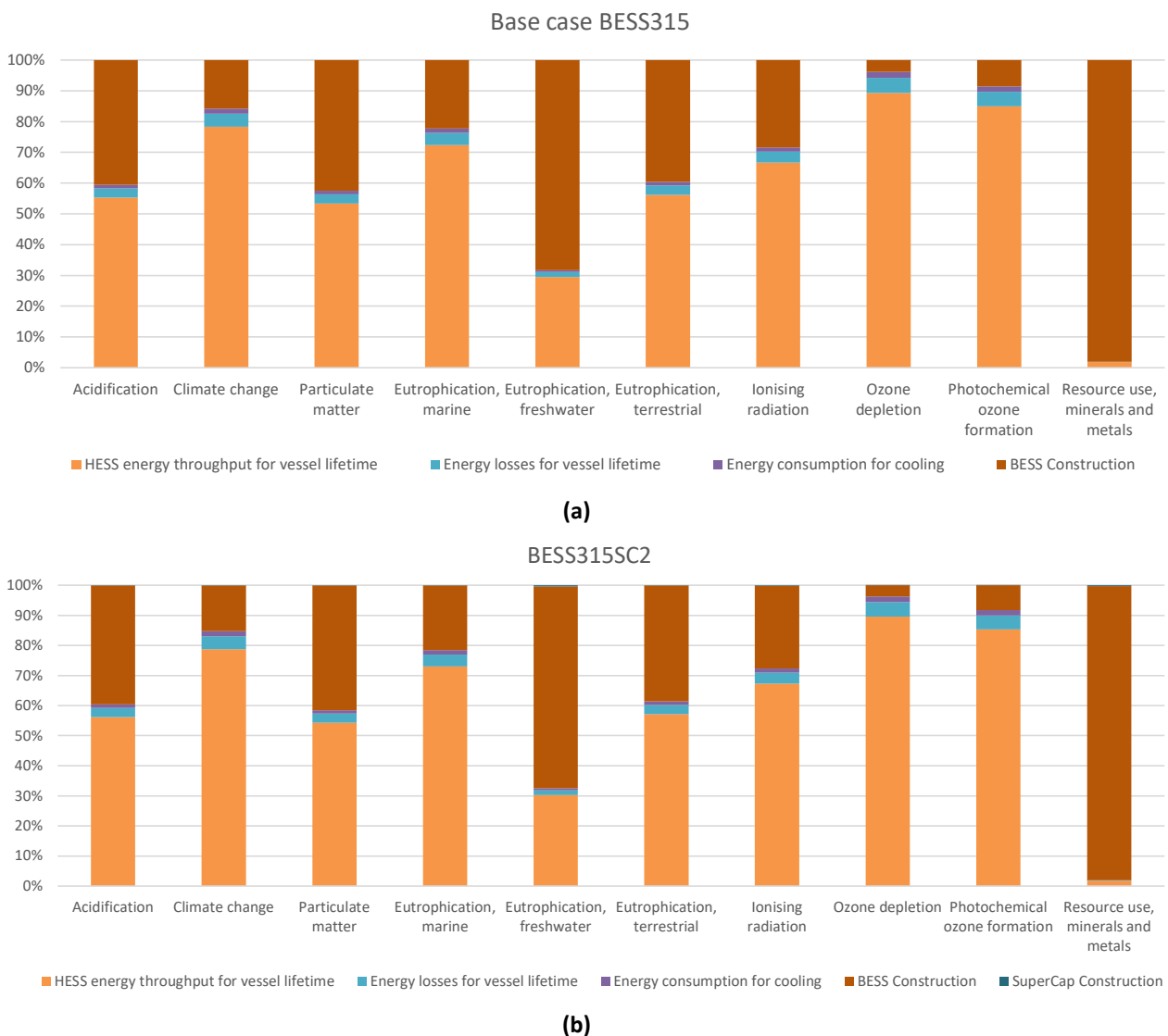


Figure 13: Life cycle impact assessment with processes contribution: (a) Base case study battery storage system with 315 installed modules for 30 years lifetime (BESS315) and (b) configuration with 315 installed battery modules and 2 Supercapacitors installed modules (BESS315SC2).

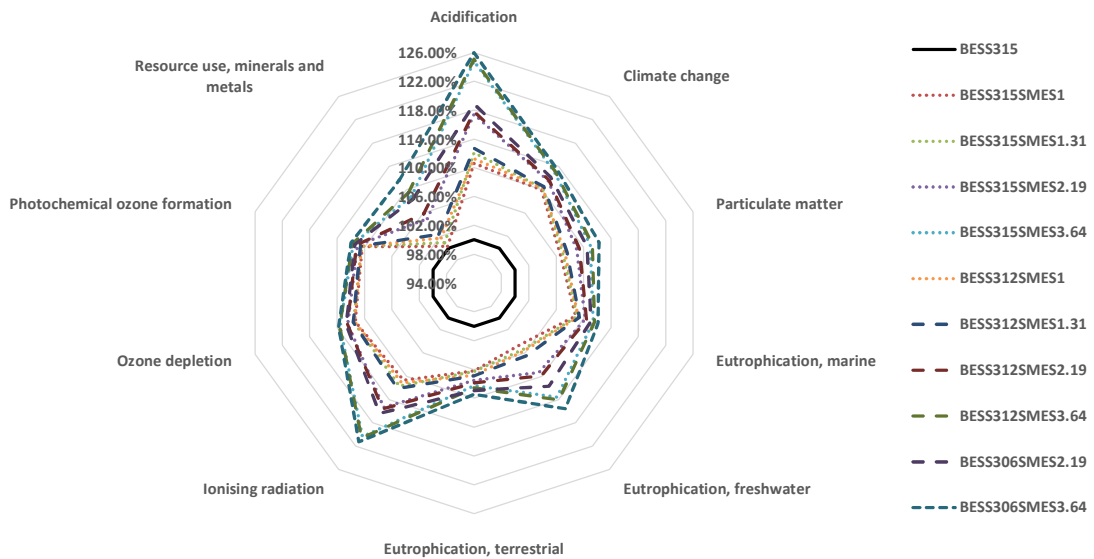


Table 34 and

Figure 14 summarize the results obtained for the trawler case, considering the assessed hybrid storage systems: BESS and SMES.

Based on the assumptions of the LCA study and the data obtained in WP1, from the life cycle impact assessment resulted that for the trawler application none of the examined V-ACCESS case studies performs better than the reference case in all the examined impact categories. BESS315SMES1 is the configuration characterized by the lower impact increase compared to the reference case, so a more detailed analysis focused on this case study. More specifically, the impacts increase with percentage ranging from 0.3% for resource use, mineral and metals up to 11.3% for ozone depletion potential category. Regarding the climate change the impact increases by 10% in BESS315SMES1 configuration compared to the reference case.

Table 35 provides a detailed life cycle impact assessment on climate change (kg CO₂ eq) for the assessed hybrid energy storage systems, subdivided by different process contributions and percentage variation compared to the reference case.

Table 34: Potential environmental impacts for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the trawler case.

		BESS	315	315	315	315	315	312	312	312	312	306	306
		SMES	-	1	1.31	2.19	3.64	1	1.31	2.19	3.64	2.19	3.64
Impact category	Acidification [mol H+ eq]		5.93E+03	6.55E+03	6.64E+03	6.96E+03	7.39E+03	6.59E+03	6.68E+03	6.98E+03	7.41E+03	7.04E+03	7.47E+03
	Climate change [kg CO ₂ eq]		1.09E+06	1.20E+06	1.20E+06	1.21E+06	1.23E+06	1.20E+06	1.20E+06	1.22E+06	1.23E+06	1.22E+06	1.24E+06
	Particulate matter [disease inc.]		4.15E-02	4.42E-02	4.44E-02	4.52E-02	4.60E-02	4.45E-02	4.46E-02	4.54E-02	4.62E-02	4.58E-02	4.66E-02
	Eutrophication, marine [kg N eq]		1.11E+03	1.21E+03	1.21E+03	1.22E+03	1.24E+03	1.21E+03	1.22E+03	1.23E+03	1.24E+03	1.23E+03	1.25E+03
	Eutrophication, freshwater [kg P eq]		2.32E+01	2.43E+01	2.45E+01	2.54E+01	2.64E+01	2.45E+01	2.47E+01	2.55E+01	2.65E+01	2.59E+01	2.68E+01
	Eutrophication, terrestrial [mol N eq]		1.25E+04	1.33E+04	1.33E+04	1.35E+04	1.36E+04	1.34E+04	1.34E+04	1.35E+04	1.36E+04	1.36E+04	1.37E+04
	Ionising radiation [kBq U-235 eq]		1.57E+04	1.74E+04	1.76E+04	1.82E+04	1.90E+04	1.75E+04	1.77E+04	1.82E+04	1.90E+04	1.83E+04	1.91E+04
	Ozone depletion [kg CFC11 eq]		1.05E-01	1.17E-01	1.17E-01	1.18E-01	1.19E-01	1.17E-01	1.17E-01	1.18E-01	1.19E-01	1.18E-01	1.19E-01
	Photochemical ozone formation [kg NMVOC eq]		1.00E+04	1.11E+04	1.11E+04	1.11E+04	1.12E+04	1.11E+04	1.11E+04	1.12E+04	1.12E+04	1.12E+04	1.12E+04
	Resource use, minerals and metals [kg Sb eq]		3.06E+01	3.07E+01	3.09E+01	3.21E+01	3.33E+01	3.11E+01	3.13E+01	3.24E+01	3.35E+01	3.32E+01	3.41E+01

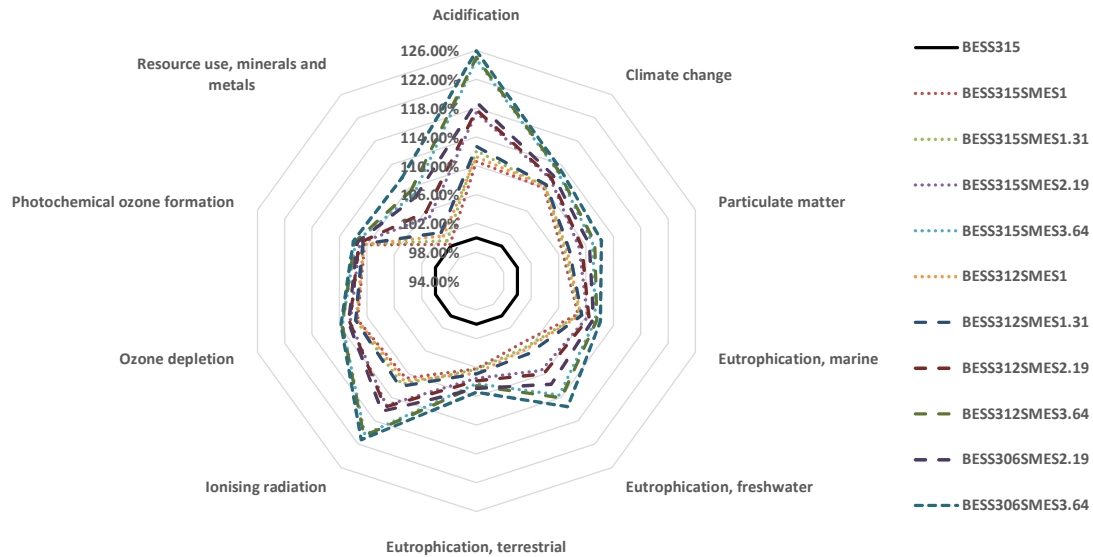


Figure 14: Graphical representation of the results obtained for the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)) for the OSV case.

The BESS315SMES1 configuration shows a 4.58% increase in construction phase impacts compared to the reference case, BESS315. The detailed analysis highlighted that although adding the SMES allows for improving the BESS state of health at the end of life (see Table 20), the related environmental benefit, in terms of reduction on impact related to BESS manufacturing, is not enough to compensate for the SMES construction impact.

As the number of SMES modules increases, energy losses decrease, demonstrating the potential of SMES technology to improve the operational phase, leading to a reduction in associated environmental impacts. However, cooling energy demand rises significantly compared to the reference case, highlighting the necessity of exploring alternative cooling methods for SMES systems to reduce energy consumption during the operational phase.

Considering BESS315SMES1 configuration as the best solution in terms of lower increase in total climate change impact, Figure 15 shows the life cycle impact assessment with processes contribution for the base case (BESS315) and this best-case configuration.

The environmental impacts across all categories are primarily driven by the electricity used for the mission, followed by the construction of the BESS and SMES, with only exception the resource use minerals and metals impact category that has as driver the BESS construction. System losses and cooling electricity also contribute smaller but notable portions to the overall impacts, with a visible impact of the SMES cooling in BESS315SMES1 configuration.

Table 35: Left side: life cycle impact assessment on climate change (kgCO₂eq) of the assessed hybrid energy storage systems (Battery energy storage system (BESS) and Superconducting Magnetic Energy Storage (SMES)), subdivided by different process contribution, for the trawler case and percentage variation compared to the reference case. Right side: fuel increase and state of health at the end of the vessel lifetime in percentage variation compared to the reference case. (Operational phase: energy for mission profile (the same for all configurations) + energy losses + energy cooling; SoH: State of Health at the end of vessel lifetime)

	Life cycle impact on climate change results										Data from WP1	
	Construction		Energy Losses		Energy for cooling		Operational phase		Total		Fuel variation	SoH
	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	kgCO ₂ eq	%	%	BESS
BESS315	1.72E+05	0.00%	4.67E+04	0.00%	1.77E+04	0.00%	9.17E+05	0.00%	1.09E+06	0.00%	0.00%	0.00%
BESS315SMES1	1.80E+05	4.58%	4.64E+04	-0.70%	1.19E+05	570.25%	1.02E+06	10.96%	1.20E+06	9.96%	10.96%	3.52%
BESS315SMES1.31	1.83E+05	6.59%	4.63E+04	-0.99%	1.18E+05	569.15%	1.02E+06	10.93%	1.20E+06	10.24%	10.93%	4.10%
BESS315SMES2.19	1.97E+05	14.81%	4.62E+04	-1.11%	1.18E+05	568.71%	1.02E+06	10.91%	1.21E+06	11.53%	10.91%	4.16%
BESS315SMES3.64	2.15E+05	25.21%	4.56E+04	-2.47%	1.17E+05	563.77%	1.02E+06	10.75%	1.23E+06	13.03%	10.75%	6.48%
BESS312SMES1	1.82E+05	6.08%	4.66E+04	-0.31%	1.19E+05	570.73%	1.02E+06	10.99%	1.20E+06	10.22%	10.99%	1.72%
BESS312SMES1.31	1.86E+05	8.05%	4.64E+04	-0.60%	1.18E+05	569.62%	1.02E+06	10.96%	1.20E+06	10.50%	10.96%	2.34%
BESS312SMES2.19	1.99E+05	15.66%	4.64E+04	-0.72%	1.18E+05	569.19%	1.02E+06	10.94%	1.22E+06	11.69%	10.94%	2.86%
BESS312SMES3.64	2.16E+05	25.91%	4.57E+04	-2.11%	1.17E+05	564.20%	1.02E+06	10.78%	1.23E+06	13.16%	10.77%	5.31%
BESS306SMES2.19	2.03E+05	18.23%	4.68E+04	0.16%	1.19E+05	570.29%	1.02E+06	11.01%	1.22E+06	12.15%	11.01%	-0.50%
BESS306SMES3.64	2.20E+05	28.11%	4.61E+04	-1.35%	1.18E+05	565.11%	1.02E+06	10.83%	1.24E+06	13.56%	10.83%	2.29%

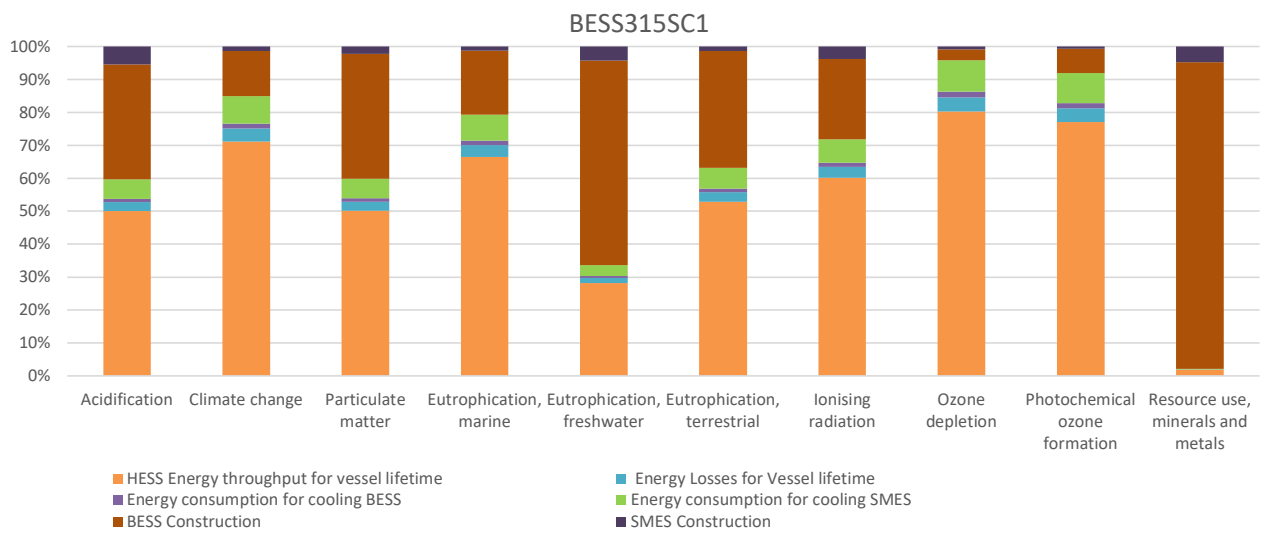
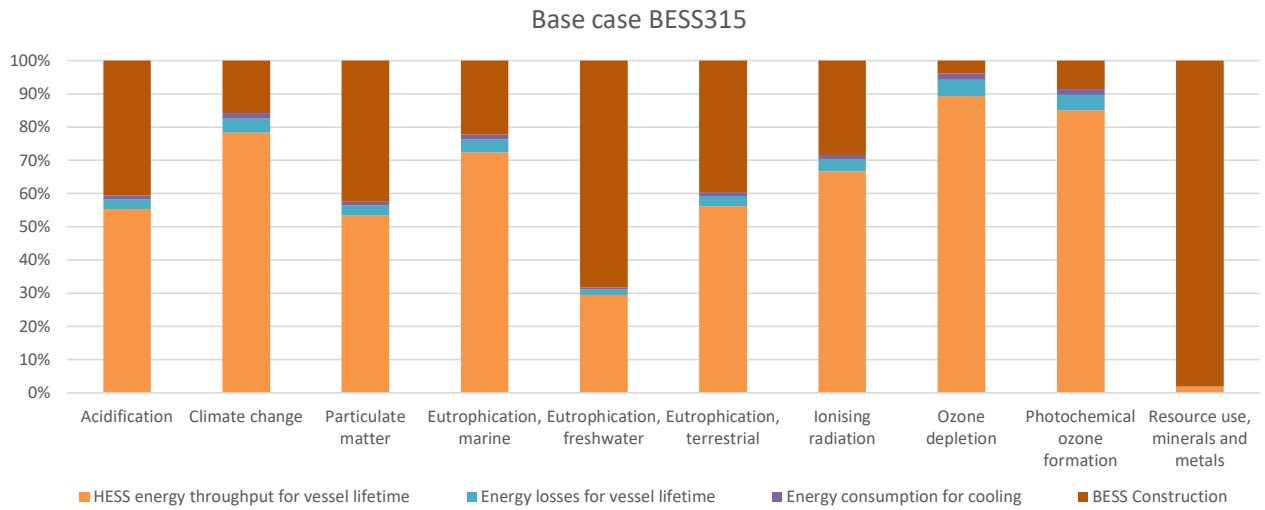


Figure 15: Life cycle impact assessment with processes contribution: (a) Base case study battery storage system with 315 installed modules for 30 years lifetime (BESS315) and (b) configuration with 315 installed battery modules and 1 Superconducting Magnetic Energy Storage (SMES) installed module (BESS315SMES1).

5.4 Commodity Life Cycle Costing (CLCC)

5.4.1 Electric Ferry - CLCC

The Figure 16 illustrates the value of the CLCC indicator calculated for the electric ferry and for each energy storage system considered. The functional unit is the same as for the LCA study.

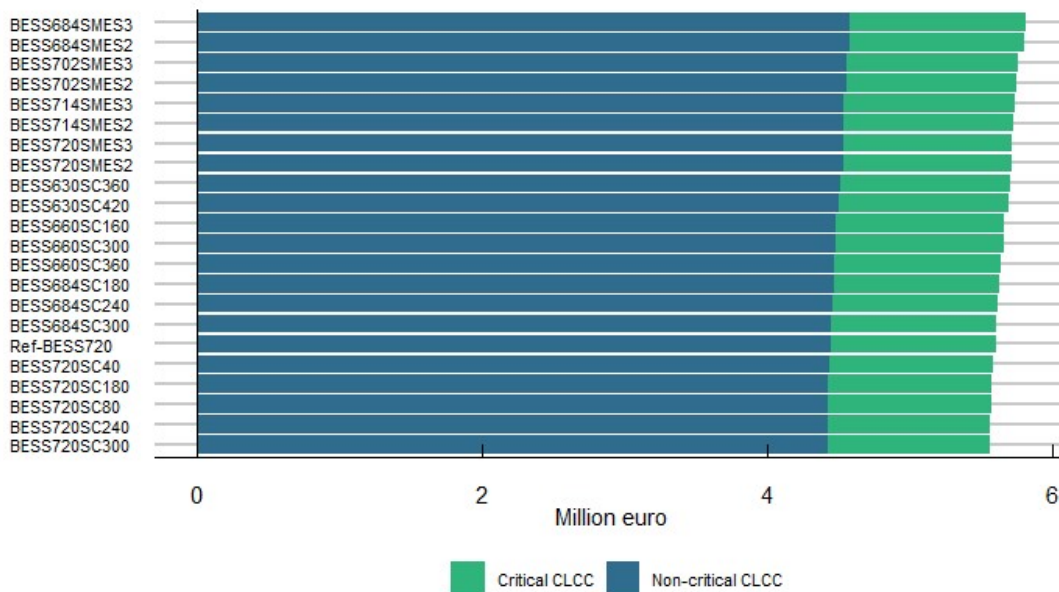


Figure 16: Ferry – Total CLCC indicator.

The energy systems considered have similar values of both the total and critical CLCC indicators. The CLCC indicator of the system characterised by the highest value (BESS684SMES3) is just 4.5% higher than that of the system with the lowest value (BESS720SC300). The difference is slightly bigger in the case of the critical indicator: the CLCC critical indicator of the BESS684SMES3 is 7.9% higher than that of the BESS720SC300 system.

The Figure 17 and the **Errore. L'origine riferimento non è stata trovata.** show the relative importance of the different life-cycle phases in the overall CLCC indicator.

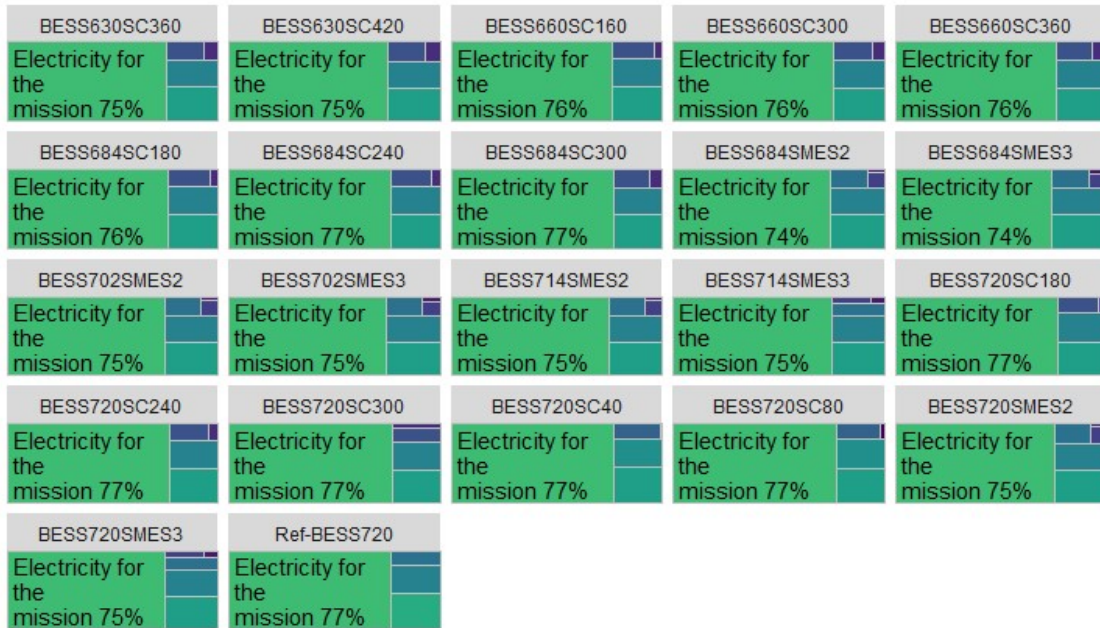


Figure 17: Relative weight of life cycle phases on the total CLCC indicator.

For all alternatives considered, electricity consumption for the mission is the phase characterized by the highest relative importance on the overall CLCC indicator. The share on total CLCC is almost 75% for all storage systems. The composition of the indicator looks very similar across all systems compared, with minor differences regarding the SMES/Super capacitor construction phases, which, of course, are not present across all alternatives.

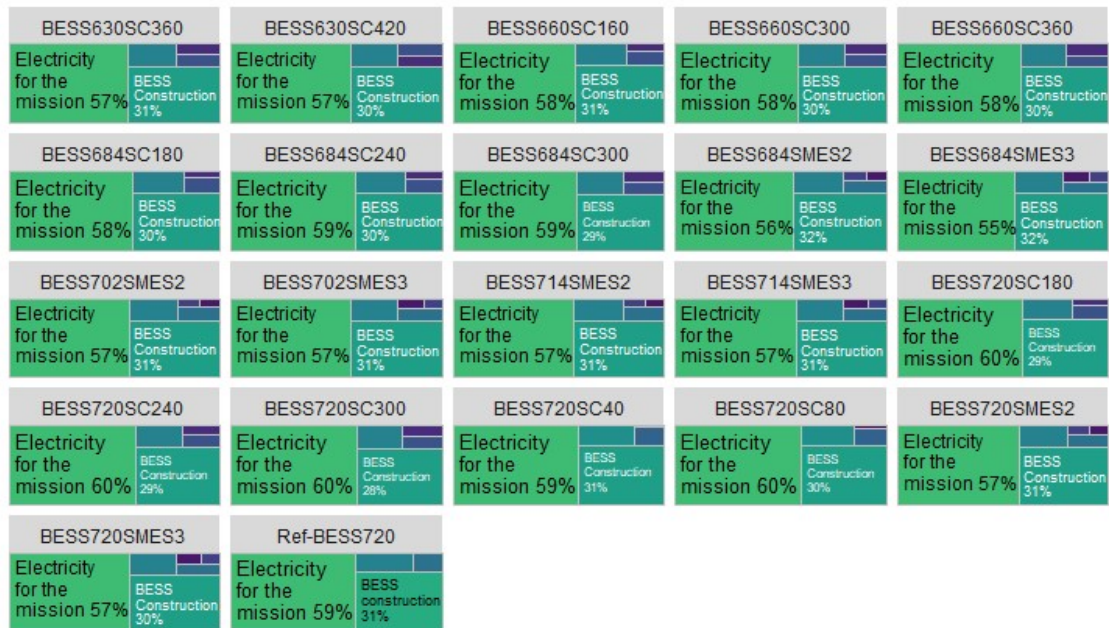


Figure 18: Relative weight of life cycle phases on the critical CLCC indicator

In the case of the critical indicator, electricity for the mission is still the phase that accounts the most (but to a lesser extent if compared to the total CLCC indicator). On the contrary, the relative importance of the BESS construction grows substantially. Similarly to the total CLCC indicator, differences across storage systems are minimal and relative to the construction phase.

Errore. L'origine riferimento non è stata trovata. show the breakdown of the total CLCC indicator by commodity. Also in this case, the picture looks similar across all alternatives, with coal and natural gas (at the basis of electricity production) representing almost 50% of the total value of the indicator. Oil, shale and wood (also inputs of electricity production) are other important commodity categories.



Figure 19: Relative weight of commodity flows on the CLCC indicator.

When it comes to the critical CLCC indicator (see Figure 20), the relative importance of coal increases almost to 60% for all storage systems considered. Coking coal, a mixture of coals suitable for coke production, is considered a critical material by the European Commission [32]. At the moment, the Ecoinvent database does not consider coking coal a primary flow. On the contrary, Ecoinvent aggregates anthracite and some bituminous coals (which encompass coking coal) into the *hard coal* flow. For this reason, it is very much likely not all coal used for electric generation is coal suitable for coke production and therefore its share of the critical CLCC indicator is overestimated. The CLCC indicator is being updated in order to overcome this problem but when this study was completed, the old version only was available.



Figure 20: Relative weight of commodity flows on the critical CLCC indicator.

Figure 21 shows the composition of the critical CLCC indicator when coal is excluded. The two most important substances are copper and nickel. Also, aluminium and silicon have a significant impact.



Figure 21: Relative weight of commodity flows on the CLCC indicator.

5.4.2 OSV – AHC - CLCC

The Figure 22 illustrates the value of the CLCC indicator calculated for the OSV and for each energy storage system considered. The functional unit is the same as for the LCA study.

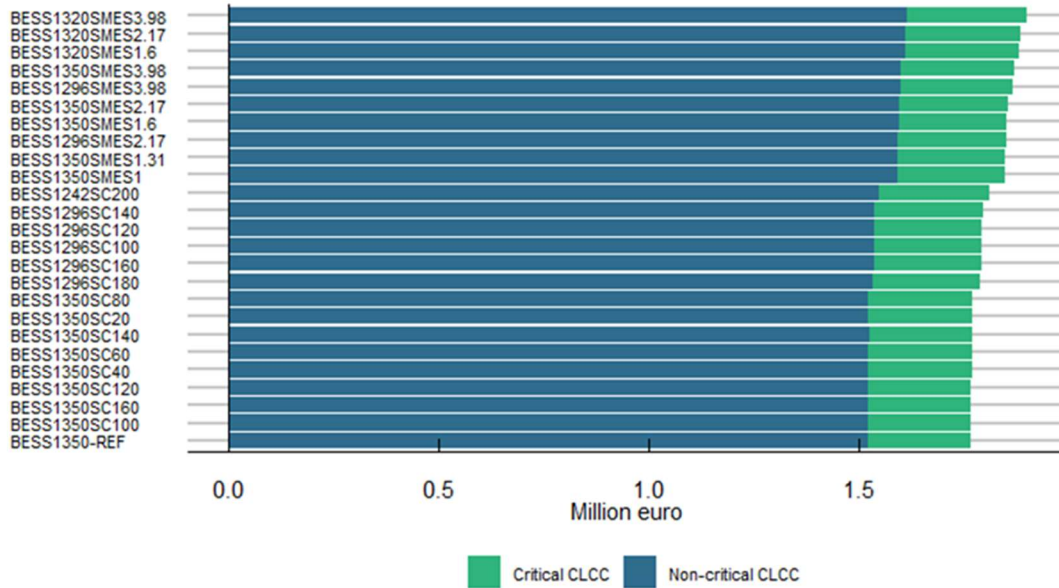


Figure 22: OSV - Total CLCC indicator.

The energy systems considered have similar values of both the total and critical CLCC indicators. The CLCC indicator of the system characterised by the highest value (BESS1320SMES3.98) is just 8.7% higher than that of the system with the lowest value (BESS1404). The difference is bigger in the case of the critical indicator: the CLCC critical indicator of the BESS1320SMES3.98 is 19.1% higher than that of the BESS1404 system.

The Figure 23 and the Figure 24 show the relative importance of the different life-cycle phases in the overall CLCC indicator.



Figure 23: Relative weight of life cycle phases on total CLCC indicator

For all alternatives considered, the BESS energy throughput accounts for as much as 63-68% of the total CLCC indicator. The picture changes when only critical material flows are considered. BESS construction is the phase that accounts for about 90% of the CLCC critical indicator, in all alternatives. Also in this case, the alternatives considered do not differ much between each other.



Figure 24: Relative weight of life cycle phases on the critical CLCC indicator.

Figure 25 shows the breakdown of the total CLCC indicator by commodity. Also in this case, the picture looks similar across all alternatives, with oil (at the basis of fuel production) representing more than 60% of the total value of the indicator.

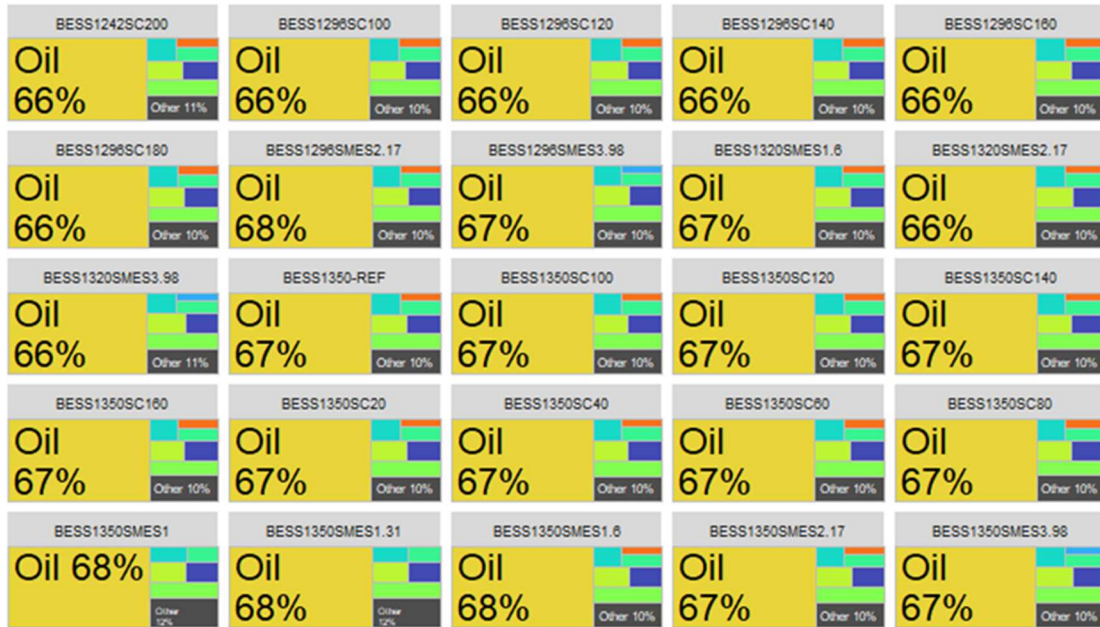


Figure 25: OSV - Relative weight of commodity flows on the CLCC indicator.

When it comes to the critical CLCC indicator (see Figure 26), the most important flows are nickel and lithium that, together, represent about 50% of the CLCC indicator value across all alternatives considered. Other important flows are copper, coal and barium, depending on the alternative considered.

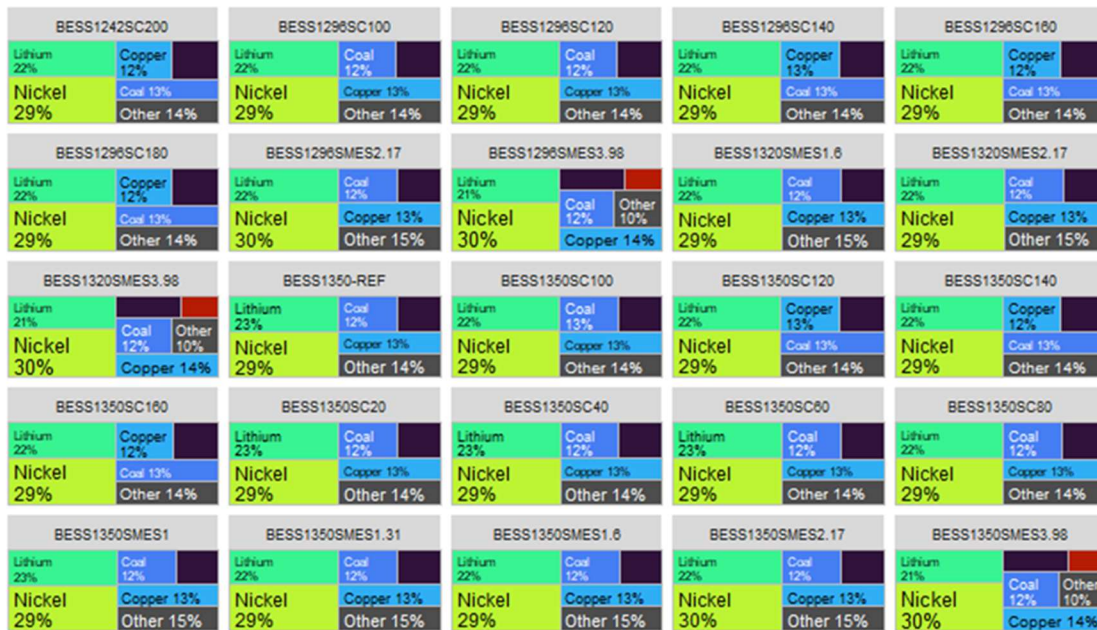


Figure 26: Relative weight of commodity flows on the critical CLCC indicator.

Figure 27 shows the composition of the critical CLCC indicator when coal (which is considered a critical raw material when used for coke production by the European Union, see section 5.4.1) is excluded. The most important substance becomes nickel.



Figure 27: OSV - Relative weight of commodity flows on the CLCC indicator.

5.4.3 Trawler - CLCC

The Figure 28 illustrates the value of the CLCC indicator calculated for the trawler and for each energy storage system considered. The functional unit is the service provided by the OSV considering a lifetime of 30 years (The boat is operated 219 days per year).

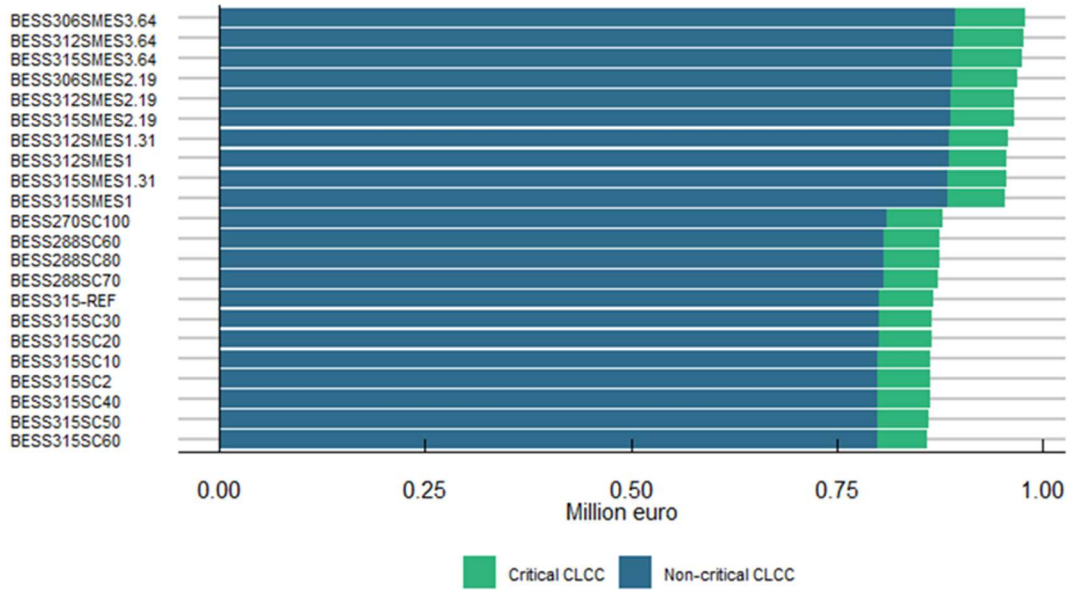


Figure 28: Trawler - Total CLCC indicator.

The energy systems considered have similar values of both the total and critical CLCC indicators. The CLCC indicator of the system characterised by the highest value (BESS306SMES3.64) is just 14.9% higher than that of the system with the lowest value (BESS360). The difference is small also in the case of the critical indicator: the CLCC critical indicator of the BESS306SMES3.64 is 45.3% higher than that of the BESS360 system.

The Figure 29 and the Figure 30 show the relative importance of the different life-cycle phases in the overall CLCC indicator.

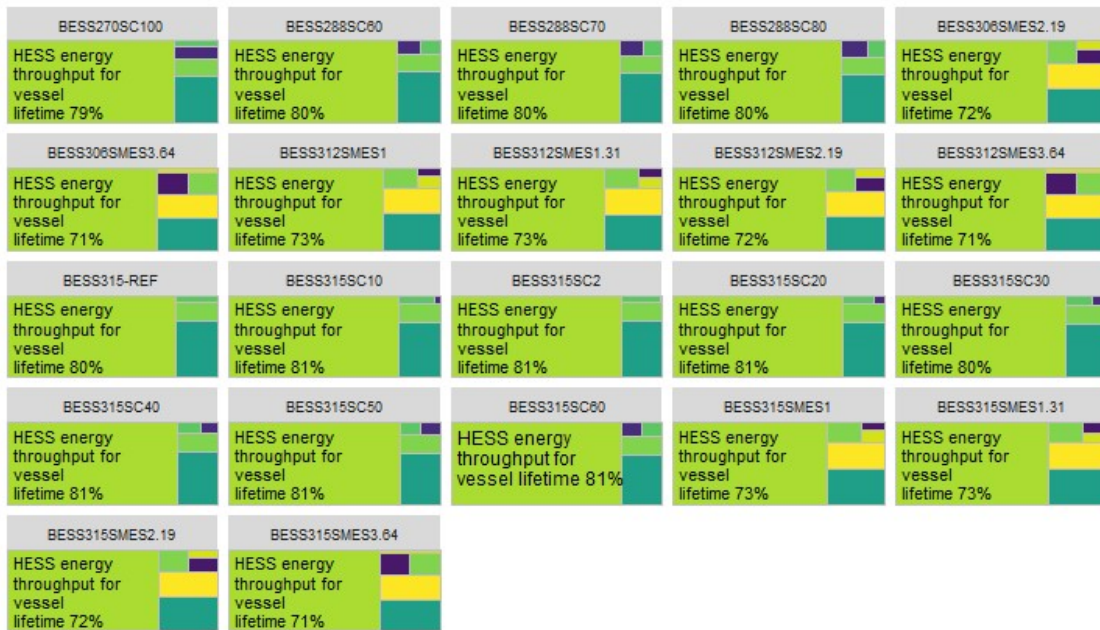


Figure 29: Trawler - Relative weight of life cycle phases on total CLCC indicator.

For all alternatives considered, the BESS energy throughput accounts for most of the total CLCC indicator, even though with some differences across alternatives. The picture changes when only critical material flows are considered. The most important phase becomes BESS construction for all alternatives, even though with some differences across alternatives.



Figure 30: Trawler - Relative weight of life cycle phases on the critical CLCC indicator.

Figure 31 show the breakdown of the total CLCC indicator by commodity. Also in this case, the picture looks similar across all alternatives, with oil representing almost 80% of the total value of the indicator.



Figure 31: Trawler - Relative weight of commodity flows on the CLCC indicator

When it comes to the critical CLCC indicator (see Figure 32), the most important flows are nickel and lithium that, together, represent about 50% of the CLCC indicator value across all alternatives considered. Other important flows are copper and coal. The relative importance of these flows varies little depending on the alternative considered.



Figure 32: Trawler - Relative weight of commodity flows on the critical CLCC indicator.

Figure 33 shows the composition of the critical CLCC indicator when coal (which is considered a critical material when used to produce coke, see section 5.4.1) is excluded. The most important substance becomes nickel, followed by barium.

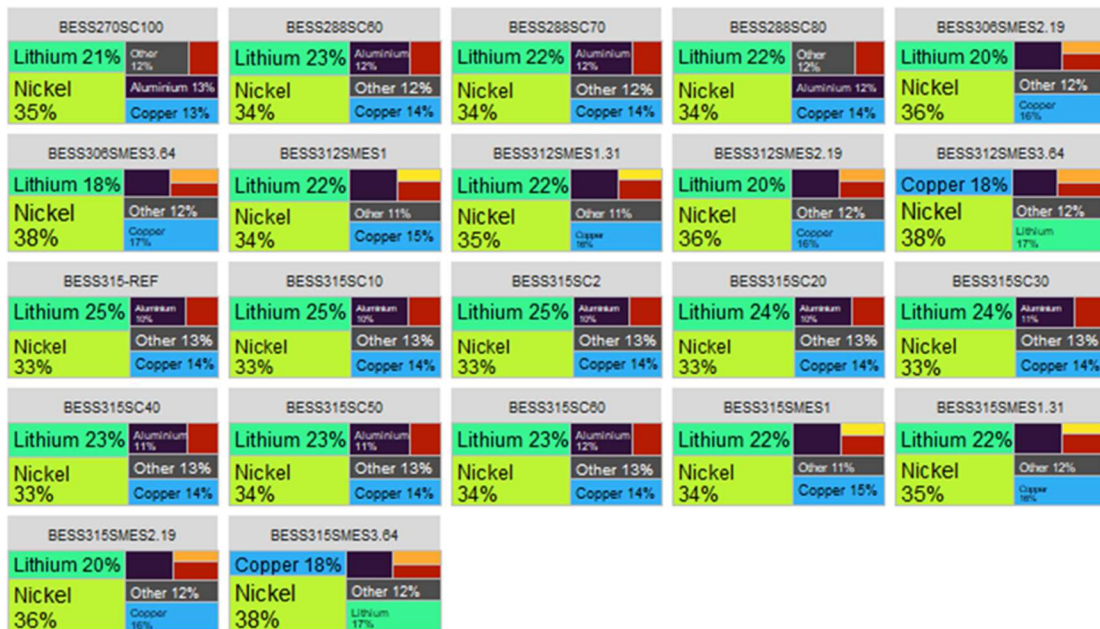


Figure 33: Trawler - Relative weight of commodity flows on the CLCC indicator.

6 Eco-design strategies for sustainability

Based on the results of the comparative LCA and the contribution analysis of individual processes to the total impacts caused by the product systems under study, it is possible to identify a variety of eco-design strategies aimed at promoting more sustainable practices in the hybridization of storage systems, specifically the integration of SC and SMES with BESS in the marine field. Several strategies can be implemented to improve outcomes in future projects:

Local Production of BESSs: The construction of BESSs within the European Union (EU) instead of relying on imports from China could significantly reduce emissions associated with transportation and production. The presence of an energy mix with a significant contribution from renewable sources can further reduce the impact on climate change. The choice of the energy mix used for the various phases of the battery life cycle can greatly influence the overall impacts. For example, in [35], it is shown that, compared to the Italian energy mix, the European mix generates slightly higher impacts (+1%), while the Chinese mix results in significantly greater impacts (+30%).

Reducing manufacturing impact: Use low-impact materials to produce the storage systems and optimize manufacturing processes. In [35] is shown that for Li-ion batteries, differences in cell design and binder type, could lead to significant variations in environmental impacts.

End-of-life (EoL) of storage systems: The EoL of storage systems can follow different paths depending on the level of degradation degree and its residual capacity, *i.e.*, the ability to store and release energy. In the case of BESS, if safety conditions for battery reuse are met and the residual capacity is significant, a second life can be considered, meaning the battery can be reused in contexts with lower performance and energy density requirements (for example, an automotive battery can be used in its second life as a stationary battery). Another EoL path involves the reuse of individual cells. It is possible that the functionality of a battery is compromised due to the malfunction of one or more cells. Battery cells that have reached the end of their life and pass durability, reliability, and safety tests can be reused as they are. Finally, a last EoL path, which can follow the previous ones, is the recycling of materials present, particularly in the cells. In this case, batteries that have reached the end of their usage phase can undergo two types of final disposal treatments: pyrometallurgical and hydrometallurgical processes. In [35], when material recycling was considered during the EoL assessment, all batteries (NMC and LFP) showed a general impacts reduction. In detail, the recycling process of NMC batteries, consisting of mechanical treatment of the modules followed by hydrometallurgical treatment of the black mass, can enable a significant reduction in the environmental impacts of both production and recycling of the batteries, thanks to environmental credits associated with the recovery of valuable metallic compounds, which can reach up to 35% in terms of climate change [36]. The scientific literature regarding the EoL of supercapacitors and SMES is not as extensive as that for BESSs; however, further research in this field is crucial to enhance the understanding and optimization of these energy storage technologies. Regarding supercapacitors, the recycling protocol proposed in literature comprehends a shredding phase and a subsequent mild thermal treatment to separate the active material from the electrodes. The objective of the treatment is to maximize the recovery of important materials such as the active material and the electrolyte [37], [38].

Design for EoL: Facilitate disassembly and component separation to enable material recovery and minimize waste.

Optimization of Alternative Storage Systems: While current battery-powered vessels (as full electric ferries) have already achieved maximum efficiency, the addition of new storage systems, such as SCs and SMES, requires further optimization to enhance their efficiency. This improvement is essential to extend battery lifespan, reduce the overall need for replacements, and thereby lower the environmental footprint.

Improve Cooling for SMES: The possible use of liquid hydrogen, already present on some vessels as a fuel for hydrogen fuel cells, as a cooling medium for SMES systems has the potential to enhance their performance and efficiency. In this context, and in specific applications, liquid hydrogen may be considered a burden-free cold source, as its cryogenic properties can be exploited to meet the cooling requirements of SMES without introducing additional environmental burdens, contributing to both energy savings and reduction of climate change impact during the operational phase.

Lifecycle phase balancing: Carefully assess trade-offs between operational benefits and manufacturing impacts to maximize the overall environmental performance of the system.

These strategies, if adopted, could contribute to a more sustainable approach to hybrid storage systems in marine applications, moving closer to the desired CO₂eq reduction targets.

7 Conclusions

The first part of this report was focalized on the update of the literature review conducted in Deliverable D4.1. This update reveals that the reviewed articles predominantly focused on battery electric vessels and hybrid marine power systems, which integrate conventional internal combustion engine generators with batteries. This highlights the need for further research into the environmental sustainability of combining batteries with superconducting magnetic energy storage and supercapacitors in marine applications, confirming further the importance of this research. The present study directly addresses this gap, thereby making a significant contribution to the existing body of literature.

The analysis of the available technical Life Cycle Assessment (LCA) guidance specific to the industrial sector, reflecting the latest updates, shows the growing interest and importance of having a clear methodology when modelling the end-of-life and recycling of ESS.

In the second part of the report, a comprehensive Life Cycle Assessment and a Commodity Life Cycle Costing assessment were conducted to evaluate both the environmental impacts and performance in terms of resource consumption of hybrid energy storage systems, specifically BESSs combined with SCs and SMES. The assessment covered three types of maritime vessels: electric ferries, offshore support vessels with active heave compensation, and trawlers. The selection of these ship types is justified by their diverse operational profiles and specific applications of energy storage system, as detailed in [16]. Ferries, operating on short and regular routes, are particularly suitable for full electric propulsion and frequent recharging in port, enabling zero-emission operation. OSV-AHC utilize EES mainly for dynamic positioning, where high-power support over limited durations improves fuel efficiency and reduces emissions. Trawlers represent a hybrid application, where EES supports various phases, such as trawling, transit, and unloading, optimizing engine load and minimizing fuel consumption. These three ship types provide representative use cases for assessing the integration and benefits of EES in maritime transport. The analysis encompasses a wide range of environmental impact categories, with particular emphasis on the climate change.

For the electric ferry, the reference case power system consists of two identical BESS units based on NMC-G lithium-ion technology, with 1,356 kWh total installed energy capacity (BESS720). In this case study, the LCA highlighted that, by maintaining the fixed capacity of the BESS and integrating a supercapacitor (SC) with a capacity ranging from 4.52 kWh to 22.6 kWh, there is a reduction in the climate change impact of up to 1% over the entire lifecycle of the BESS. This reduction is obtained for the configuration in which a 22.6 kWh supercapacitor is integrated (BESS720SC300 configuration). This configuration is identified as the optimal one, not only for climate change impact but also across other environmental categories, where a reduction in impact of the same magnitude is observed compared to the reference case. Furthermore, the analysis of alternative configurations, with a lower BESS capacity and higher supercapacitor capacity, resulted in higher impacts across all environmental categories. Furthermore, the contribution analysis revealed that in this configuration, the climate change impact associated with the BESS manufacturing phase is reduced by 11.5% due to the higher state of health of the BESS at end of life (+6.84% compared to the reference case) and hence a lower battery substitution rate. However, the addition of the supercapacitor increases the construction phase impact of the overall power system (BESS+SC) by 14%. The operational energy impact, which includes energy for the mission, energy losses, and energy required for cooling, is reduced by 1.1%

overall. Finally, this configuration avoids a total of 255.09 tons of CO₂ equivalent, which is equivalent to the annual energy use of 31.1 homes⁸.

Regarding the integration of BESS with SMES for the electric ferry, the LCA study showed that all configurations examined have greater impacts across all categories. The optimal configuration identified is the one with the same BESS installed capacity as the reference case and a SMES with an installed capacity of 834 Wh (BESS720SMES3 configuration), which results in a 1.8% increase in the overall climate change impact. This configuration results in a reduction in climate change impact due to lower efficiency losses; however, this benefit is offset by the higher impacts associated with the energy required for cooling the SMES. Therefore, a potential solution to enhance the performance of this hybrid power system (as liquid hydrogen) could be to deploy it in applications where a burden-free energy source is available for cooling the SMES.

For the ferry case, the analysis of total and critical CLCC indicators revealed that the energy systems considered have similar values for both indicators. The system with the highest total CLCC indicator (BESS684SMES3) is only 4.5% higher than the system with the lowest value (BESS720SC300). The electricity consumption for the mission phase is the most significant contributor to the overall CLCC indicator, accounting for nearly 75% of the total value. In terms of critical materials, coal and natural gas are the most important commodities, representing almost 50% of the total indicator value.

For the offshore support vessel with active heave compensation, the reference case power system consists of a BESS units based on LFP-G lithium-ion technology, with an installed energy capacity of 1,170 kWh (1,350 BESS modules) (BESS1350). In this application the hybrid power storage system, *i.e.* BESS integrated with SC, performs worse than the reference case in almost all the examined environmental categories. Exceptions are represented by the acidification, terrestrial eutrophication, particulate matter, and resource use, minerals and metals, in which some configurations show slightly better performance. Concerning climate change, the configuration with the lowest impact increase consists of a BESS with the same installed capacity as the reference case (+0.35%) and a supercapacitor of 2.26 kWh (BESS1350SC20 configuration). This configuration shows impacts in the other environmental categories that are generally aligned with those of the reference case, slightly higher, but not significantly different in percentage terms. This configuration is characterized by a negligible reduction of the impact related to the improvement of the BESS state of health at the end of life and of the operational phase that are both offset by the impact associated to the supercapacitor. The contribution analysis of the different configurations revealed that, in the case of the system with an installed supercapacitor capacity of 18.08 kWh (BESS1350SC160), the impact associated with the BESS construction phase is reduced by 7%, while the operational energy impact—which includes mission energy, energy losses, and cooling requirements—decreases by 0.24% compared to the reference case. However, these benefits are offset by the additional environmental burden introduced by the construction of the supercapacitors. As a result, the overall climate change impact of this configuration increases by 1.30% relative to the reference scenario.

To mitigate this increase, several strategies can be considered. One approach involves reducing the environmental impact of manufacturing by using low-impact materials in supercapacitor production and optimizing the associated industrial processes. Another strategy focuses on end-of-life design, promoting

⁸ Greenhouse Gas Equivalencies Calculator (www.epa.gov/energy/greenhouse-gas-equivalencies-calculator)

easier disassembly and separation of components to facilitate material recovery and minimize waste. Finally, a balanced evaluation of the different life cycle phases is essential, where trade-offs between operational benefits and manufacturing impacts are carefully assessed to maximize the system’s overall environmental performance.

Regarding the integration of BESS with SMES for the OSV-AHC application, the LCA study showed that all configurations examined result in higher environmental impacts across all impact categories. Notably, none of the configurations demonstrate a reduction in climate change impact during the operational phase. In configurations where the BESS has the same energy capacity as the reference case (1170 kWh) and is combined with a 2.255 kWh SMES (BESS 1350SMES3.98), a slight reduction in the impact associated with BESS construction is observed, due to the improved state of health at end-of-life. However, this benefit is negligible when compared to the increased impact caused by the construction of the SMES, energy losses due to lower system efficiency, and, most significantly, the substantial energy demand required for cooling the SMES.

For the OSV case, the system with the highest total CLCC indicator (BESS1320SMES3.98) is 8.7% higher than the system with the lowest value (BESS1404). The BESS energy throughput phase accounts for 63-68% of the total CLCC indicator. When considering critical materials, nickel and lithium are the most significant, together representing about 50% of the critical CLCC indicator value.

For the trawler, the reference case power system consists of a BESS units based on LFP-G lithium-ion technology, with an installed energy capacity of 273 kWh (315 BESS modules) (BESS315). In this application, some of the examined configurations of the hybrid power storage system that integrates the BESS, and the supercapacitor reduce the impact in some environmental categories compared to the reference case study. In detail, in the configuration with the same BESS installed capacity as the reference case (BESS315) and a SC with an installed capacity of 0.226 kWh the impact on climate change decreases by 0.58% compared to the reference case. The contribution analysis highlighted that the integration of the supercapacitor (SC) allows a 4% reduction in climate change impacts related to BESS manufacturing, due to the improved state of health at the end of life. While the construction of the supercapacitor introduces additional impacts, the overall balance remains positive, with a net 3.5% reduction in climate change impacts thanks to the extended battery lifetime and hence lower substitution rate. Additionally, this configuration results in a 0.4% decrease in the impact associated with the operational phase. The contribution analysis of the other configurations showed that the setup with a 273 kWh BESS and a 6.78 kWh SC (BESS315SC60 configuration) allows for a 0.34% reduction in impacts associated with the operational phase. However, in this case, the benefits are outweighed by the impacts related to the manufacturing of a larger SC. Configurations featuring a smaller BESS and a larger SC, on the other hand, exhibit worse performance across all impact categories. Regarding the integration of BESS with SMES for the trawler application, the LCA study showed that all configurations examined result in higher environmental impacts across all impact categories. Notably, none of the configurations demonstrate a reduction in climate change impact during the operational phase.

These findings demonstrate that while hybrid energy storage systems offer potentially small benefits in specific configurations, their overall environmental performance strongly depends on the sizing and integration strategy of the components involved. Future research and development should therefore focus

on optimizing these configurations, with particular attention to material selection, system efficiency, and end-of-life strategies, in order to fully unlock the environmental advantages of hybrid storage solutions in the maritime sector, if any.

For the trawler case, the energy systems exhibited similar values for the total and critical CLCC indicators. The system with the highest total CLCC indicator (BESS306SMES3.64) is 14.9% higher than the system with the lowest value (BESS360). The BESS energy throughput phase is the most significant contributor to the total CLCC indicator. For critical materials, nickel and lithium are the most important, together accounting for about 50% of the critical CLCC indicator value.

Overall, the study investigated the potential of hybrid energy storage systems to reduce environmental impacts in maritime applications. The best configurations for each vessel type demonstrated slight reductions in CO₂ emissions and improvements in battery health. To further enhance environmental sustainability, it is recommended to investigate if it is possible to optimize the number of supercapacitor or SMES modules to achieve a balance between performance and environmental impact. Additionally, exploring alternative cooling methods for SMES systems could reduce energy consumption during the operational phase. The results also highlight the importance of the energy throughput phase in the overall CLCC indicator and the significant role of critical materials such as nickel and lithium in the critical CLCC indicator.

The results from the three case studies indicate that, with current technologies, hybrid ESS offer limited environmental advantages over BESS in maritime applications. However, the findings suggest that with further technological advancements and optimization, hybrid systems could play a more meaningful role in enhancing both environmental and operational performance.

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9 APPENDIX

9.1 Documents Analysed for Marine Applications in Deliverable D4.1.

Table 36 - Documents regarding marine applications analysed within the bibliographic review presented in Deliverable D4.1.

Reference	Marine application and ship type	Technology/Power system
Chin-Ling, J., Roskilly, A.P., 2016. 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 [39]	Roll on/roll off cargo ship	Hybrid power system: 6 diesel gensets plus cold-ironing, PV, and lithium-ion battery systems
Maritime Battery Forum, 2016. Life cycle analysis of batteries in maritime sector [40].	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, 2017. Life Cycle Assessment of a Battery Passenger Ferry [41].	Passenger ferry	Battery
Jeong, B., et al., 2018. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems [42].	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., 2020. Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity [43].	Roll on/roll off (ro-ro) passenger ship	Battery: Lithium-ion batteries (Battery capacity: 830 kWh)
Perčić, M., et al., 2020. Life-Cycle Cost Assessment of Alternative Marine Fuels to Reduce the Carbon Footprint in Short-Sea Shipping: A Case Study of Croatia [44]	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., 2020. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector [45].	Roll-On-Roll-Off-Passenger passenger vessel operating in short-sea shipping sector	Lithium-ion battery
Wang H., et al., 2021. Life cycle analysis and cost assessment of a battery powered ferry [46].	Fast catamaran ferry	LiNiMnCo ₂ battery
Fan et al., 2021. Decarbonising inland ship power system: Alternative solution and assessment method [47]	Inland ships (Canal ship consisting of a 64 TEU container ship and river ship consisting of a 6700 tons 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., 2021. Electrification of Inland Waterway Ships Considering Power System Lifetime Emissions and Costs [48].	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., 2022. Life-cycle assessment and life-cycle cost assessment of power	Ro-Ro passenger ferry, very short (ship1), medium (ship	Pb-acid, Ni-MH, and Lithium-ion battery technologies

batteries for all-electric vessels for short-sea navigation [49].	2) and relative long route (ship3)	
Park, C., et al., 2022. Live-Life cycle assessment of the electric propulsion ship using solar PV [50]	RoPax ferry	Case1: Diesel-electric operation Case2: Full battery mode Case3: Full battery with a solar PV system
Kim, S., et al., 2022. Lifecycle Environmental Benefits with a Hybrid Electric Propulsion System Using a Control Algorithm for Fishing Boats in Korea [51].	Fishing boats (4.99 tons, 9.77 tons, and 47 tons)	Battery hybrid system that uses both an engine and a battery
Kanchiralla, et al., 2022. Life-Cycle Assessment and Costing of Fuels and Propulsion Systems [52].	Roll-On-Roll-Off-Passenger (RoPax) vessel	Battery
Jeong, B., et al., 2022. Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole? [53]	Short-route ferries	Battery
Park, C., et al., 2022. Lifecycle energy solution of the electric propulsion ship with Live-Life cycle assessment for clean maritime economy [54].	Hybrid Ro-Pax ferry	Case1: Electric propulsion ship with Diesel generator engine 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., 2023. Life-cycle assessment and life-cycle cost assessment of lithium-ion batteries for passenger ferry [55].	Passenger ferry	Lithium-ion batteries (NMC532, NMC622, NMC811, NCA, LFP)
Manouchehrinia, B., et al., 2018 Emission and life cycle analysis of hybrid and pure electric propulsion systems for fishing boats [56].	Lobster fishing vessels	HESS: SC+ICE (Gasoline); SC+ICE (Diesel); BESS+ICE (Gasoline); BESS+ICE (Diesel) Pure battery (electric powered) Conventional ICE (gasoline and diesel)

9.2 Inventory

Table 37 – Inventory data for the production of 1 kg of Li-ion battery for the ferry case. The source of information used is mentioned in the name.

Dataset name	Quantity	Unit	Source	Comment
Output				
Li-Ion NMC Battery for Ferry case	1	kg		
Input				
Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U	0.0029	kg		
Steel, chromium steel 18/8 {GLO} market for steel, chromium steel 18/8 Cut-off, U	0.3244	kg		
Li-Ion battery production_Battery cell LBV Alloc Rec, U_Ellingsen	0.4368	kg	[57]	
Battery management system, for Li-ion battery {GLO} battery management system production, for Li-ion battery Cut-off, U	0.0242	kg		
Battery module packaging, Li-ion {GLO} market for battery module packaging, Li-ion Cut-off, U	0.1316	kg		
Copper, anode {GLO} market for copper, anode Cut-off, U	0.0013	kg		
Electronic component, passive, unspecified {GLO} market for electronic component, passive, unspecified Cut-off, U	0.0103	kg		
Ethylene glycol {GLO} market for ethylene glycol Cut-off, U	0.0215	kg		
Glass fibre reinforced plastic, polyamide, injection moulded {GLO} market for glass fibre reinforced plastic, polyamide, injection moulded Cut-off, U	0.0004	kg		
Impact extrusion of steel, cold, 1 strokes {GLO} market for impact extrusion of steel, cold, 1 strokes Cut-off, U	0.3244	kg		
Injection moulding {GLO} market for injection moulding Cut-off, U	0.01	kg		
Metal working factory {GLO} market for metal working factory Cut-off, U	1.4141E-09	p		
Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate Cut-off, U	0.01	kg		
Reinforcing steel {GLO} market for reinforcing steel Cut-off, U	0.0148	kg		
Sheet rolling, aluminium {GLO} market for sheet rolling, aluminium Cut-off, U	0.0029	kg		
Sheet rolling, copper {GLO} market for sheet rolling, copper Cut-off, U	0.0009	kg		
Sheet rolling, steel {GLO} market for sheet rolling, steel Cut-off, U	0.0148	kg		
Tap water {RoW} market for tap water Cut-off, U	0.0215	kg		
Electricity, medium voltage {CN} market group for electricity, medium voltage Cut-off, U	0.0002	kWh		

Table 38 Inventory data for the production of one SuperCapacitor Rack. The source of information used is mentioned in the name.

Dataset name	Quantity	Unit	Source	Comment
Output				
SuperCap Rack (DE)	550	kg		
Input				
SuperCap module {DE} SuperCap production Cut-off, U	330	kg		

Battery management system, for Li-ion battery {GLO} market for battery management system, for Li-ion battery Cut-off, U	20.35	kg		
Li-ion battery production_cooling system Alloc Rec, U_Ellingsen	22.55	kg	[57]	
Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U	176	kg		
Metal working, average for steel product manufacturing {RER} metal working, average for steel product manufacturing Cut-off, U	176	kg		
Switch, toggle type {GLO} market for switch, toggle type Cut-off, U	1.1	kg		

Table 39 Inventory data for the production of one SuperCap Module. The source of information used is mentioned in the name.

Dataset name	Quantity	Unit	Source	Comment
Output				
SuperCap Module (DE)	33	kg		
Input				
SuperCap cell (DE)	27	kg		
Battery module packaging, Li-ion {GLO} market for battery module packaging, Li-ion Cut-off, U	6	kg		

Table 40 Inventory data for the production of one SuperCap Cell. The source of information used is mentioned in the name.

Dataset name	Quantity	Unit	Source	Comment
Output				
SuperCap cell (DE)	0.465	kg		
Input				
Slurry components for SuperCap {CN} eletrodes production	0.07	kg		Positive electrode paste
Slurry components for SuperCap {CN} eletrodes production	0.056	kg		Negative electrode paste
Aluminium collector foil, for Li-ion battery {GLO} market for aluminium collector foil, for Li-ion battery Cut-off, U	0.0304	kg		Positive electrode – 1.5 m ²
Aluminium collector foil, for Li-ion battery {GLO} market for aluminium collector foil, for Li-ion battery Cut-off, U	0.0304	kg		Negative electrode – 1.5 m ²
Kraft paper {RoW} market for kraft paper Cut-off, U	0.0167	kg		Proxy for cellulose separator
Acetonitrile {GLO} market for acetonitrile Cut-off, U	0.172	kg		Proxy for electrolyte TEABF4 1M
Supercap cell container tab and terminals Alloc Rec, U	0.1245	kg		
Electricity, medium voltage {DE} market for electricity, medium voltage Cut-off, U	5	kWh		
Waste to treatment				
Waste electric and electronic equipment {GLO} market for waste electric and electronic equipment Cut-off, U	0.035	kg		

Table 41 Inventory data for the production of the electrode paste.

Dataset name	Quantity	Unit	Source	Comment
Output				
Slurry components for SuperCap {CN} eletrodes production	0.126	kg		
Input				
Carbon black {GLO} market for carbon black Cut-off, U	0.0035	kg		
Chemical factory, organics {GLO} market for chemical factory, organics Cut-off, U	4E-10	p		
Carboxymethyl cellulose, powder {RER} carboxymethyl cellulose production, powder Cut-off, U	0.0024	kg		
Acrylic binder, with water, in 40% solution state {RoW} market for acrylic binder, with water, in 40% solution state Cut-off, U	0.0029	kg		Own elaboration starting from ecoinvent dataset: Acrylic binder, with water, in 54% solution state {RoW} acrylic binder production, with water, in 54% solution state Cut-off, U
Activated carbon, granular {GLO} market for activated carbon, granular Cut-off, U	0.1179	kg		
Water, deionised {Europe without Switzerland} market for water, deionised Cut-off, U	0.1953	kg		
Emissions to air				
Water	0.1953	kg		

Table 42 Inventory data for modelling the manufacturing process of a SMES with a rated energy capacity of 200 Wh, weight approximately 1000 kg.

Dataset name	Quantity	Unit	Source	Comment
Output				
SMES	1	p		
Input				
Cryostat for SMES	401.1	kg		
Cryocooler RDK-415D2 4K for SMES	40	kg		
Cable, Superconducting coil (MgB2) {EU} cable production Cut-off, U	200	kg		
Current lead for SMES	5.005	kg		
Copper, cathode {GLO} market for copper, cathode Cut-off, U	50	kg		proxy for heat conduction plate
Air compressor, screw-type compressor, 4kW {GLO} market for air compressor, screw-type compressor, 4kW Cut-off, U	0.71	p		
Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U	5	kg		mechanical supports
Copper, cathode {GLO} market for copper, cathode Cut-off, U	5	kg		mechanical supports

Glass fibre {GLO} market for glass fibre Cut-off, U	1	kg		
Refrigerator {GLO} market for refrigerator Cut-off, U	3.33	p		proxy for chiller
Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U	60	kg		proxy for mandrel
Metal working, average for steel product manufacturing {RER} metal working, average for steel product manufacturing Cut-off, U	65	kg		
Pump, 40W {GLO} market for pump, 40W Cut-off, U	2	p		proxy for vacuum
Metal working, average for copper product manufacturing {GLO} market for metal working, average for copper product manufacturing Cut-off, U	55	kg		

Table 43 Detailed inventory data for the construction of the cryostat.

Dataset name	Quantity	Unit	Source	Comment
Output				
Cryostat for SMES	401.1	kg		
Input				
Steel, chromium steel 18/8 {RER} steel production, electric, chromium steel 18/8 Cut-off, U	400	kg		
Acrylonitrile-butadiene-styrene copolymer {GLO} market for acrylonitrile-butadiene-styrene copolymer Cut-off, U	0.1	kg		
Fibre, polyester {GLO} market for fibre, polyester Cut-off, U	1	kg		

Table 44 Detailed inventory data for Cryocooler.

Dataset name	Quantity	Unit	Source	Comment
Output				
Cryocooler RDK-415D2 4K for SMES	401.1	kg		
Input				
Steel, chromium steel 18/8 {GLO} market for steel, chromium steel 18/8 Cut-off, U	17.5	kg		
Copper, cathode {GLO} market for copper, cathode Cut-off, U	1	kg		

Table 45 Detailed inventory data for the production of the Superconducting cable. Data provided by ASG Superconductors.

Dataset name	Quantity	Unit	Source	Comment
Output				
Cable, Superconducting coil (MgB2) {EU} cable production Cut-off, U	109.25	kg		
Input				
Monel {RER} nickel-copper alloy production Cut-off, U	65	kg		
Extrusion, plastic pipes {GLO} market for extrusion, plastic pipes Cut-off, U	38.916	kg		
Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate Cut-off, U	38.916	kg		
Rolling mill {GLO} market for rolling mill Cut-off, U	1.7695E-12	p		

Tap water {GLO} market group for tap water Cut-off, U	166.98	kg		
Magnesium {RoW} magnesium production, electrolysis Cut-off, U	5	kg		
Nickel, class 1 {GLO} market for nickel, class 1 Cut-off, U	40	kg		
Boric oxide {GLO} market for boric oxide Cut-off, U	5	kg		
Electricity, high voltage {IT} Electricity mix 2018 Alloc Rec, U - RSE Sistema	13000	kWh	Modelling provided in [58]	
Emissions to air				
Water/m3	0.0102	m3		
Emissions to water				
Water, GLO	0.1568	m3		

Table 46 Detailed inventory data for Monel production.

Dataset name	Quantity	Unit	Source	Comment
Output				
Monel {RER} nickel-copper alloy production Cut-off, U	1	kg		Own elaboration starting from ecoinvent dataset "iron-nickel-chromium alloy {RER} iron-nickel-chromium alloy production Cut-off, U
Input				
Anode, for metal electrolysis {GLO} market for anode, for metal electrolysis Cut-off, U	0.003	kg		
Electric arc furnace converter {RER} electric arc furnace converter construction Cut-off, U	4E-11	p		
Copper, cathode {GLO} market for copper, cathode Cut-off, U	0.32	kg		
Hard coal {Europe, without Russia and Turkey} market for hard coal Cut-off, U	0.014	kg		
Natural gas, high pressure {CH} market for natural gas, high pressure Cut-off, U	0.0002	m3		
Natural gas, high pressure {Europe without Switzerland} market group for natural gas, high pressure Cut-off, U	0.0248	m3		
Nickel, class 1 {GLO} market for nickel, class 1 Cut-off, U	0.68	kg		
Oxygen, liquid {RER} market for oxygen, liquid Cut-off, U	0.0507	kg		
Quicklime, in pieces, loose {CH} market for quicklime, in pieces, loose Cut-off, U	0.055	kg		
Refractory, basic, packed {GLO} market for refractory, basic, packed Cut-off, U	0.0135	kg		

Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U	0.425	kWh		
Emissions to air				
Benzene	0.00000228	kg		
Benzene, hexachloro-	0.00000002	kg		
Cadmium (II)	3.65E-08	kg		
Carbon monoxide, fossil	0.00232	kg		
Chromium (III)	0.00000125	kg		
Copper, ion	0.00000023	kg		
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	4.54E-12	kg		
Hydrocarbons, aromatic	0.000077	kg		
Hydrochloric acid	0.0000052	kg		
Hydrogen fluoride	0.00000235	kg		
Lead (II)	0.00000181	kg		
Mercury (II)	0.00000224	kg		
Nickel (II)	0.0000007	kg		
Nitrogen oxides	0.00018	kg		
PAH, polycyclic aromatic hydrocarbons	3.72E-08	kg		
Particulates, < 2.5 um	0.000166	kg		
Particulates, > 10 um	0.0000586	kg		
Particulates, > 2.5 um, and < 10um	0.000166	kg		
Polychlorinated biphenyls	2.32E-08	kg		
Sulfur dioxide	0.000077	kg		
Zinc (II)	0.0000229	kg		
Waste to treatment				
Electric arc furnace dust {RER} market for electric arc furnace dust Cut-off, U	0.0051	kg		
Electric arc furnace slag {RER} market for electric arc furnace slag Cut-off, U	0.0768	kg		
Inert waste, for final disposal {CH} market for inert waste, for final disposal Cut-off, U	0.005	kg		

Table 47 Inventory data for Current lead for SMES.

Dataset name	Quantity	Unit	Source	Comment
Output				
Current lead for SMES	1	kg		
Input				
Copper, cathode {GLO} market for copper, cathode Cut-off, U	5	kg		
Metal working, average for copper product manufacturing {GLO} market for metal working, average for copper product manufacturing Cut-off, U	5	kg		

Table 48 Inventory data for 1 kg of LFP Battery production.

Dataset name	Quantity	Unit	Source	Comment
Output				
Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {GLO} market for battery, Li-ion, LFP, rechargeable, prismatic Cut-off, U	1	kg		
Input				
Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {CN} battery production, Li-ion, LFP, rechargeable, prismatic Cut-off, U	0.3096	kg		
Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {RoW} battery production, Li-ion, LFP, rechargeable, prismatic Cut-off, U¹	0.6904	kg		
Transport, freight train {GLO} market group for transport, freight train Cut-off, U	0.3091	tkm		
Transport, freight, inland waterways, barge {GLO} market group for transport, freight, inland waterways, barge Cut-off, U	0.0246	tkm		
Transport, freight, lorry, unspecified {GLO} market group for transport, freight, lorry, unspecified Cut-off, U	0.2088	tkm		
Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U	0.5990	tkm		

Table 49 Inventory Data for 1kg of LFP Battery produced in China.

Dataset name	Quantity	Unit	Source	Comment
Output				
Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {CN} battery production, Li-ion, LFP, rechargeable, prismatic Cut-off, U	1	kg		
Input				
Aluminium, wrought alloy {GLO} market for aluminium, wrought alloy Cut-off, U	0.0036	kg		
Steel, chromium steel 18/8 {GLO} market for steel, chromium steel 18/8 Cut-off, U	0.4113	kg		
Battery cell, Li-ion, LFP {GLO} market for battery cell, Li-ion, LFP Cut-off, U	0.3036	kg		
Battery management system, for Li-ion battery {GLO} battery management system production, for Li-ion battery Cut-off, U	0.0201	kg		
Battery module packaging, Li-ion {GLO} market for battery module packaging, Li-ion Cut-off, U	0.1696	kg		
Copper, anode {GLO} market for copper, anode Cut-off, U	0.0016	kg		
Electronic component, passive, unspecified {GLO} market for electronic component, passive, unspecified Cut-off, U	0.0106	kg		
Ethylene glycol {GLO} market for ethylene glycol Cut-off, U	0.0255	kg		
Glass fibre reinforced plastic, polyamide, injection moulded {GLO} market for glass fibre reinforced plastic, polyamide, injection moulded Cut-off, U	0.0005	kg		
Impact extrusion of steel, cold, 1 strokes {GLO} market for impact extrusion of steel, cold, 1 strokes Cut-off, U	0.4114	kg		
Injection moulding {GLO} market for injection moulding Cut-off, U	0.0117	kg		

Metal working factory {GLO} market for metal working factory Cut-off, U	1.15E-09	p		
Polyethylene, high density, granulate {GLO} market for polyethylene, high density, granulate Cut-off, U	0.0117	kg		
Reinforcing steel {GLO} market for reinforcing steel Cut-off, U	0.0216	kg		
Sheet rolling, aluminium {GLO} market for sheet rolling, aluminium Cut-off, U	0.0037	kg		
Sheet rolling, copper {GLO} market for sheet rolling, copper Cut-off, U	0.0016	kg		
Sheet rolling, steel {GLO} market for sheet rolling, steel Cut-off, U	0.0216	kg		
Tap water {RoW} market for tap water Cut-off, U	0.0255	kg		
Electricity, medium voltage {CN} market group for electricity, medium voltage Cut-off, U	0.0002	kWh		

¹ Dataset for **Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {RoW}| battery production, Li-ion, LFP, rechargeable, prismatic | Cut-off, U** modelled following the same datasets and quantities at **Battery, Li-ion, LFP for V-ACCESS, rechargeable, prismatic {CN}| battery production, Li-ion, LFP, rechargeable, prismatic | Cut-off, U**, only Electricity providers have been kept different following the original dataset **Battery, Li-ion, LFP, rechargeable, prismatic {RoW} | market for battery, Li-ion, LFP, rechargeable, prismatic | Cut-off, U**.