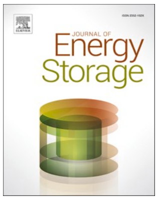
Journal of Energy Storage 87 (2024) 111440

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



Review article

Lessons learned from the commercial exploitation of marine battery energy storage systems

Wei He [a,*], Lars O. Valøen [b], Kjetil V. Olsen [c], Kåre M. Kjeka [c], Bjørn M. Fredriksen [c], Mathieu Petiteau [d], Amine Touat [d], Helge Såtendal [a], Aaron Howie [a], David Howey [e], Rambabu Kandepu [b], Carsten F. Hammershøj [a]

[a] *Technology, Digital and Innovation, Equinor, 4035 Stavanger, Norway*
[b] *Corvus Energy, 5224 Nesttun, Norway*
[c] *Solstad Shipping ASA, Nesavegen 39, 4280 Kopervik, Norway*
[d] *Ponant, 408 avenue du Prado, 13008 Marseille, France*
[e] *Engineering Science Dept., University of Oxford, Parks Rd., Oxford OX1 3PJ, UK*

ARTICLE INFO

Keywords:
Battery
Energy storage
Hybrid
Supply vessel
Fuel saving
Cruise ship

ABSTRACT

Large, reliable, and economically viable battery energy storage systems (BESSs) play a crucial role in electrifying the maritime industry. In this paper, we draw from the experiences of over 750 recent commercial marine BESS installations to bridge the gap between research findings and industrial needs in four key areas: (i) Decision-making for installations: We introduce a go/no-go-decision matrix for assessing the feasibility of installations in a maritime context. (ii) Safe and cost-effective installations: This study evaluates the risks and expenses associated with these BESS installations, including retrofitting a 500 kWh BESS (total costs: 1.3 million euros; 2600 euros per kWh), installing a 4.5 MWh BESS (5 million euros; 1100 euros per kWh), and an unsuccessful attempt to retrofit an 800 kWh BESS. (iii) Operation analysis: We delve into the operational outcomes of BESSs deployed on 47 offshore supply vessels (OSVs) (ranging from 452 to 1424 kWh) and a large 4.5 MWh BESS on a newly constructed cruise ship. The application of the equivalent full cycle (EFC) method reveals that the operational EFCs were notably lower than the designed EFCs. The proposed two new evaluation criteria assess the annual fuel saving resulting from BESS installed per kWh and per EFC. Over a two-year period, the 4.5 MWh BESS demonstrated fuel saving of 1–2 % as compared to the 5 % target. Addressing converter losses during low-power BESS operation modes necessitates further investigation. (iv) Further development: This study advocates for research aimed at enhancing safety measures, exploring onshore/offshore power supply and charging, optimizing multi-objective operations, and progressing towards zero emissions. The insights gathered in this paper can serve as a valuable resource for ship support ship owners and operators seeking to kick-off faster or to install more BESSs on their vessels and optimize their operational effectiveness.

1. Introduction

The European greenhouse gas (GHG) strategy envisages a reduction in the carbon intensity of international shipping of up to 55 % by 2030 [1]. Intensified, collaborative research to achieve the intended CO$_2$ reductions, which in turn helps to pave the way towards achieving net-zero GHG emissions within Europe by 2050, is necessary in this respect. BESSs have been identified as one of the promising technologies that will contribute towards achieving the targets.

BESSs could be excellent enablers of CO$_2$ emission reductions through the electrification of the waterborne sector, e.g., ferries, some short-distance freight services, and inland waterway vessels can be successfully fully electrified [2]. A commercial large-scale rollout of BESSs across the entire spectrum of waterborne transport poses different

---

* Corresponding author.
E-mail addresses: weih@equinor.com (W. He), lvaloen@corvusenergy.com (L.O. Valøen), kjetil.olsen@solstad.com (K.V. Olsen), kare.magne.kjeka@solstad.com (K.M. Kjeka), bjorn.fredriksen@solstad.com (B.M. Fredriksen), mpetiteau@ponant.com (M. Petiteau), atouat@ponant.com (A. Touat), hesat@equinor.com (H. Såtendal), ahowi@equinor.com (A. Howie), david.howey@eng.ox.ac.uk (D. Howey), rkandepu@corvusenergy.com (R. Kandepu), cfh@equinor.com (C.F. Hammershøj).

https://doi.org/10.1016/j.est.2024.111440
Received 6 October 2023; Received in revised form 24 February 2024; Accepted 20 March 2024

challenges than those experienced with the rollout in automotive sector. The main differences include: (i) lower total numbers and much more diverse types of ships; (ii) long vessel lifetimes (several decades) compared to automobiles (one or two decades), hence the number of retrofits to existing vessels being approximately 10 times higher than the number of new vessels being built, (iii) very different installation and operational conditions for waterborne fuel-saving solutions compared with in theory similar land transport scenarios, and (iv) a need for advanced technologies and large investments to properly establish a comprehensive and reliable onshore/offshore power supply and charging infrastructure.

Better alignment of BESSs and their applications with the current and future needs of the waterborne sector requires collaboration across different disciplines, industrial sectors, and geographic regions to be more effective overall. Previous work on energy storage for marine applications has discussed the benefits and drawbacks of BESS, including issues with both charging and limited capacity, and consideration for applications beyond backup power [3]. Considerable research has been undertaken on the sizing and control of marine BESS, including hybrid systems that account for battery degradation [4,5] as well as the consideration of fully-electric propulsion [6]. The onshore power supply and charging is one of the first steps towards unlocking emission reductions in this sector [7] and is being actively developed around the world. The future offshore power supply and charging are expected to have high impact on fuel-saving. Equinor has recently published one patent combining the offshore electricity supply and charging and fuel refuelling using subsea structure [8]. One research paper [9] presents a useful data-based energy management method for a hybrid vessel with fuel cell and BESS and one recent review paper presents the lithium-ion batteries integration for enabling the energy transition in shipping industry [10]. Furthermore, the learning from battery fire accidents is important for BESS commercialization projects. For example, the lessons learned from two battery fire accidents in Norway [11,12] show that battery suppliers and regulations should have a very robust safety framework, not only on single cell and module level, but also on vessel level.

However, there are still considerable gaps between the results obtained from many BESS R&D finds and the industrial needs for BESS commercial exploitation in the four key areas: (i) Decision-making for installations, (ii) Ensuring safety and cost-effective installations, (iii) Operation analysis and (iv) Further development. This disconnect has occurred as research institutions often experience difficulties in accessing the operational data and lessons learned from commercial exploitation of marine BESSs.

Previous lessons learned from operational BESS data have been shared by Equinor and Corvus [13] based on their activities in the ongoing Norwegian OMB6 project (Optimizing marine battery operations using 6 year's operational data from two commercially operating vessels) [14]. Here, we add to the existing Norwegian national collaborative effort by expanding the five Norwegian BESS research and industrial partners to 11 partners from six European countries, and by sharing lessons learned from the commercial exploitation of more than 750 BESSs. This study forms part of the on-going four-year European collaborative innovation project NEMOSHIP (NEw MOdular electrical architecture and digital platform to optimize large battery systems on SHIPs) [15]. (New electrical architecture and digital platform for optimizing large BESS on ships) [15]. In this paper, several of the NEMOSHIP project partners, namely Equinor (large offshore project developer), Corvus Energy (major marine BESS supplier), and Solstad and Ponant (two BESS ship owners/operators) have shared the latest BESS installation and operational experiences and the lessons learned openly to contribute to research activities towards accelerating BESS commercial development.

2. Objectives

We draw from the experiences of over 750 recent commercial marine BESS installations to bridge the gap between research findings and industrial needs in four key areas as follows:

- Decision-making for installations. We introduce a structured and transparent decision matrix for assessing the feasibility of installations in a maritime context.
- Safe and cost-effective installations. This study evaluates the major risks and expenses associated with three installations, including (i) retrofitting a 500 kWh BESS onto one OSV; (ii) installing a 4.5 MWh BESS onto a new-build cruise ship, and (iii) an unsuccessful attempt to retrofit an 800 kWh BESS onto an older cruise ship.
- Operation analysis. We delve into the operational outcomes of BESSs deployed on 47 OSVs (ranging from 452 to 1424 kWh) and a large 4.5 MWh BESS installed onboard a newly constructed cruise ship. This study uses the EFC method to quantify battery actual charge throughput and defines new evaluation criteria to assess the effectiveness of the fuel savings.
- Further development. This study advocates for research aimed at enhancing safety measures, exploring onshore/offshore power supply and charging, optimizing multi-objective operations, and progressing towards zero emissions.

3. Approach

This section introduces the scope and assumptions of the study, the three systems which provide the BESS operational data and the EFC method. Two new evaluation criteria have been defined to assess the effectiveness of BESS installations. Furthermore, the BESS installation to achieve a low carbon ship focuses on three aspects.

3.1. Scope and assumptions

This study focuses on BESS onboard hybrid vessels and their actual operational results along with support from onshore power when onshore power supply was available. The lessons learned are gathered from (i) more than 750 BESS commercial projects delivered by Corvus up to the end of March 2023 and (ii) installations and operational results from the BESSs on 47 OSVs and on two cruise ships.

Many offshore vessels e.g., for offshore oil and gas platforms, cannot currently be fully electrified due to their long-range offshore requirements and the weight/volume limitations on the vessels themselves. The operational strategies as well as the energy management for efficiently using BESS in a hybrid system are often more complicated than for a fully electrified vessel. There is also a greater potential in improving the BESS operations on hybrid vessels by efficient energy management than on fully electrified vessels. Finally, it is noted that as a result of the expected growth of offshore activities (for example offshore wind farms, aquaculture and offshore mining), the number of OSVs will have to increase in order to properly fulfill their facilitating role.

This study focuses on two types of hybrid systems: (i) diesel-battery for OSVs, and (ii) liquified natural gas (LNG)-battery for cruise ships. Firstly, hybrid OSVs with diesel-battery setups were used since these OSVs experience more challenges when employing BESS than ferries. This study will dive into the 500 kWh BESS retrofitted onto the Normand Sun (NS) and its five-year of operations. Secondly, two cruise ships owned by Ponant have been used to showcase the experiences and lessons learned from both a 4.5 MWh BESS installation on the newly built cruise ship “Le Commandant Charcot” (LCC) in 2021, and an unsuccessful attempt at retrofitting an 800 kWh BESS onboard an older cruise ship ‘Le Ponant’ (LP).

3.2. Data logging systems

This study extracts the operational results from three sources (i) two operational platforms: Maress [16] and Marorka [17] used by the ship owners/operators Solstad and Ponant respectively; Both Maress and Marorka provide real-time measurement of the fuel consumption onboard; and (ii) the Corvus data logging system (called Lighthouse) which monitors battery performance [18]. More specifically:

- Solstad and many OSV ship operators in Norway use the Maress platform. Maress is a webpage and database-based system that collects data gathered from several existing data sources associated with vessels. 'Maress Monthly' displays the vessel operational routes and important fuel variables including fuel used, fuel saved, increased efficiency, CO_2 saved, and shore power used for the last month. The summary report provides the total operational results for the whole operational period.
- Ponant in France uses the Marorka platform which provides energy management and reports operational performance results. The platform collects automatically logged and manually reported data from the onboard platform. It can also receive data from third party systems which collects and transmits onboard data to help reduce fuel consumption, emissions, and operating costs, while also improving safety and compliance.
- The Corvus Lighthouse logging system aims at monitoring and guidance to shipowners on how the BESS is operating to help achieve its designed lifetime. The logged data is sampled at about 1 s sampling rate. The Lighthouse data logging portal reports the parameters including average EFC, the EFC on the latest day, the battery state of health (SOH), the battery pack inlet temperature, and the module temperature.

3.3. EFC method

This study uses a practical EFC method to measure battery cyclic aging. The EFC formula calculates the number of cycles experienced by the BESS and the depth of each cycle. The multiple and variable cycles occurring within a period (e.g., day) are converted to EFCs, where the original cycles are weighted against their contribution to the aging of the BESS.

The EFC method is simple and straightforward for giving a quick assessment on the comparison between the real-world number of daily EFCs experienced and the intended number of daily EFCs of the original design. However, there are no guidelines published on how the originally recorded cycles should be weighted and converted to EFCs. As a first step, Corvus is developing and implementing a simplified EFC calculation method which has no weighting implemented in the conversion to EFCs. Moreover, the implemented EFC method has not taken into account (i) the calendar aging, and (ii) the aging stress factors such as temperature, magnitude of current, state of charge (SOC) levels and to some degree micro cycles.

3.4. Defining new evaluation criteria

EFC does not directly reflect the fuel savings resulting from the BESS installation. This study therefore defines new evaluation criteria to assess the effectiveness of the fuel savings resulting from a given BESS installation, e.g., annual fuel saving per kWh of battery installed. By adding in the fuel price and BESS costs, it paves the way for a financial analysis to be undertaken. This study also defines another new evaluation criteria including EFC, e.g., annual fuel saving per kWh per EFC.

3.5. BESS installation required to achieve a low carbon ship

The BESS installation to achieve a low carbon ship focuses on three aspects: (i) using BESS as spinning reserve capacity to reduce the number of diesel or gas generators active during dynamic position (DP) mode, (ii) hybrid vessels that are able to run only from BESS within zero emission areas including port areas (e.g. within 20 NM) and arctic areas (where approx. 2 h BESS only operation is possible), and (iii) when the ship is stationary at port, powered only by onshore power supply (no diesel generator in operation) in this case, BESS enhances ride-through, having UPS-like functionality, like spinning reserve in a local subsystem.

4. Decision-making for installations

This section develops structured and transparent methodologies/tools to support decision-making for installations and propose a go/no-go matrix which quantitatively weighs major factors based on learnings gained from the commercial exploitation of BESSs.

4.1. Requirements to develop decision-making for installations

Marine batteries are still an emerging business and the more than 750 BESSs delivered by Corvus have all been installed within the last five years (2018–2023). These BESSs account for more than 60 % of the total marine BESS market in Europe as of the end of April 2023. All involved stakeholders, special ship owners/operators, spent considerable time learning how to overcome various barriers towards initiating and going through BESS installation go/no-go decisions. The BESS installation go/no-go decision involves more than the industry's economic BESS installation criteria e.g., return on investment (ROI). The decision also considers the policies, the technologies including battery sizing based on different operational strategies and degradation profiles, and increasingly important safety issues. Many of the 750 BESSs projects have received governmental support. To the authors' knowledge, there are no structured or transparent decision methodologies/tools available to support decision-making for BESS installations in maritime context so far.

A considered approach towards evaluating retrofit/installation decision-making for BESS on OSVs/cruise ship is required. Well-structured and effective methodologies/tools tailored to decision-making by ship owners/operators, for example Solstad and Ponant, will considerably improve their forthcoming go/no-go decisions. For those companies newly starting with BESS installations, the go/no-go decision methodologies/tools can enhance the experience replicability and consequently accelerate BESS installations through standardised scenarios applicable to (i) similar vessels, (ii) across sectors, and (iii) across regions.

4.2. Major factors determining go/no-go decisions

Reviewing more than 750 BESS projects, the major factors determining go/no-go decisions can be divided into four categories: (i) Policy and regulations, (ii) Investment benefits, (iii) Operational benefits, and (iv) Safety. The major factors under these four categories are discussed as follows.

Firstly, policies and regulations are often the top incentives towards installing BESSs. Equinor launched a requirement that all the OSVs working for its oil and gas installations at Norwegian Continental Shelf should have lowest emissions before March 2019. All 18 OSVs under Equinor's long-term contracts have installed BESSs. Solstad's NS, one of these 18 OSVs, installed one 500 kWh BESS in 2018.

Ponant decided to implement the installation of a large BESS of 4.5 MWh onto its cruise ship LCC for several reasons. The top priority was to be able to achieve two-hours of no emission operations within an arctic environmental protected zone and to secure the operation of the dual-fuel engines running on gas.

Secondly, installation of BESS can be expensive and time-consuming. The cost of retrofitting a BESS onto an OSV is often twice as much as the cost of the BESS container itself, and it can take months or years of preparation before the actual retrofitting can be carried out. As a result, most of these 750 BESS projects benefited from the government financial supports.

Thirdly, the operational benefits are very important for fully commercial (unsubsidised) systems. The more than 750 BESSs are distributed across six vessel categories (Table 1) and seven applications (Table 2). Table 3 shows that the vessels with large BESS installations have achieved significant fuel and emission reductions for all six types of vessels.

Finally, there are many concerns from the ship owner/operators' prospective. One of the largest barriers slowing down BESS installations in vessels are the onerous safety requirements that must be met for the certification and re-registration of flags, especially for retrofitted vessels. Many certificates are required after BESS installation, including comprehensive failure mode and effects analysis (FMEA).

4.3. *Go/no-go decision matrix*

This study proposes a BESS installation go/no-go decision matrix to quantitatively the major factors affecting decisions discussed in previous Section 4.2.

Table 4 shows one example of main factors and scores of BESS installation go/no-go decision matrix. These factors and scores in Table 4 are based on all authors' experiences and estimations. The structured and transparent methodologies to determine these factors and scores should be further developed based on learnings gained from large commercial exploitation of BESSs.

Policies and regulations are often the main incentives to install BESSs. Governmental support impacts the financial benefits e.g., ROI. Operational benefits include O&M cost reduction, fuel savings, and CO_2/NO_x emission reductions, which all have increasing importance for ship owners/operators. When the total scores from all four categories in Table 4 are lower than a defined number, there will be a no-go decision. The major factors, the scores, and the threshold depend on the individual BESS installation conditions and should be adjusted for each project.

Applying the go/no-go decision matrix in Table 4 for the 500 kWh BESS retrofitting decision on NS, the scores in the four categories are: (i) Policy and regulations (winning vessel rental contracts): 10; (ii) Financial benefits, When the ship owner/operator receives governmental financial support of 0.5 M€, a score of 10 might show investment benefits. (iii) Operational benefits: 10, and (iv) Safety: 5. The total score was 35. If the threshold of the no-go criterion was 20, the decision would be to go ahead with the project (35 > threshold).

When the go/no-go decision matrix was applied on LP, a high-risk score of −10 under “safety” for an 800 kWh BESS installed onto an old vessel due to lack of flag approval in Table 4 should result in a showstopper for the overall project.

There are different scores for the main factors under the four categories associated with retrofitting and installing BESS on different types of vessels.

This example shows that collaboration between design company, ship owner, integrator, shipyard, maritime organization, operators, BESS supplier, and class/flag and design company is required to initiate BESS installations on commercially operating ships in a suitable way.

Due to limited experience at the start of this research, not all the advantages of decision-making using a decision matrix as an instrument have yet been fully exploited. Further experience is needed to improve the quality of go/no-go decision-making regarding the application of BESS on ships, i.e., to make decision-making more transparent, traceable, and explainable. Furthermore, the decision matrix is not only trained by the lessons learned from previous but also continuously learns from the latest maritime BESS projects in the real world.

Table 1
758 BESS projects divided into six vessel categories.

Car & passenger ferries	Cruise & yachts	Offshore & subsea	Tugs/ workboat/ fishing/ research	Merchant vessels	Port equipment/ shore stations etc.
158	42	142	152	78	186

Table 2
BESS applications.

Application	Effectiveness
Spinning reserve	Backup energy, reducing number of running engines, increasing fuel efficiency
Dynamic performance	Instant power supply, mitigate slow engine response
Peak shaving	Reduce power peaks, optimizing engine load
Zero emission	No running engines, no emissions/noise
Enhanced ride through	UPS-like functionality, like spinning reserve in local subsystem
Strategic loading	Optimize energy generation, reduce fuel consumption
Energy regeneration	Optimize use of energy from lifting operation, fuel saving

5. Safe and cost-effective installations

To gain insight into the main safety risks and the expenses involved in 500 kWh BESS retrofitting onto one OSV, a 4.5 MWh BESS installation on a newly constructed cruise ship and an attempt to retrofit one 800 kWh BESS onto an older cruise ship.

5.1. *Retrofitting one 500 kWh BESS onto one OSV*

This section analyses a 500 kWh BESS retrofitted onto NS in 2018 as shown in Fig. 1, which shows the NS, the hoisting of the BESS on board the NS and the BESS location on board the NS. The key facts of the retrofitting are listed in Table 5. The total cost was 1.3 million euros (2600 euros per kWh) and the delivery time was six months from the ordering of the BESS to the completion of the installation onboard NS. The installation and commissioning onboard took three weeks including both sea trials and FMEA for classification.

The 500 kWh BESS retrofit onto the NS consists of the following major six aspects: (i) installation plans, (ii) preparation at shipyard, (iii) preparation on OSV, (iv) delivery of 500 kWh containerized BESS, (v) installation and commissioning, and (vi) tests, certifications, and flag registrations.

The total retrofit costs of 1.3 million euros were more than 2.5 times the cost of the 500 kWh containerized BESS which was 0.5 million euros in 2018 approximately. Retrofitting the 500 kWh BESS onto NS needs many custom designs which resulted in both high installation costs and high potential failure risks for NS owner. Accordingly, modularity and standardization are required to reduce these costs and risks.

5.2. *Ponant's 4.5 MWh BESS installation onto a new cruise ship*

Ponant is a French cruise company with 13 cruise ships currently in operation and its Polar Exploration Passenger Vessel LCC (Fig. 2) was built in 2021 by the Norwegian shipyard VARD. The vessel is equipped with 6 dual fuel engines using LNG as fuel stored in membrane tanks of 4500 m^3 to supply an electrical propulsion system.

At the beginning of the project during the concept-design phase, many questions had to be clearly asked and answered to help in defining the needs and the proper dimensioning of the BESS. This process led to the installation of a 4.5 MWh ORCA series BESS manufactured and delivered by Corvus Energy to support the onboard electrical grid.

Here, two BESS units of 2260 kWh each have been connected on either side of the 11 kV main switchboard in two dedicated energy storage rooms. The footprints, weight, and costs of the 4.5 MWh BESS installation on LCC are listed in Table 6. It is noted that the total

Table 3
Reported and estimated O&M, fuel, and emission reductions per vessel category.

	Fully electric Car ferry	Hybrid Car ferry	Hybrid OSV	Fully electric Tug	Hybrid Fishing vessel	Hybrid Shuttle tanker
O&M cost reductions	80 %	35–50 %	35–50 %	80 %	50–75 %	35–50 %
Fuel saving	100 %	15–40 %	15–20 %	100 %	20–25 %	20–25 %
CO_2 emission reductions	95 %	15–40 %	15–20 %	95 %	20–25 %	20–25 %
NO_x emission reductions	95 %	30–60 %	30–40 %	95 %	30–40 %	30–40 %

Table 4
One example of main factors and scores of BESS installation go/no-go decision matrix.

Categories	Main factors	Scores (−10 to +10)
Policy & regulations	Winning vessel rental contracts	10 (e.g., 500 kWh BESS retrofitting on NS)
	Zero emissions operations within an arctic environmental protected zone	10 (e.g., installing 4.5 MWh BESS on LCC)
	Zero emissions at port (optional)	5
Investment benefits	Return on investment (ROI)	10 (e.g., NS received 0.5 M€)
	Governmental financial support	
Operational benefits	O&M cost reduction	Total operational benefit score: 10
	Fuel saving	
	CO_2 emission reductions	
	NO_x emission reductions	
Safety	Certifications	−10
	Re-registration of flags	−10 (e.g., the 800 kWh BESS could not be installed onto LP due to lack of flag approval)
	Increasing safe operations preventing black outs	5
No-go criterion		Total score < x (e.g., 20)

installation cost of the 4.5 MWh was nearly 5 million euros which results in 1100 euros per kWh normalized cost, which is much lower than the 2600 euros per kWh seen when retrofitting a 500 kWh onto the NS. As expected, installing a BESS onto a vessel that has taken this into account during design and construction is much cheaper than retrofitting a BESS onto an existing vessel. In addition, the larger the capacity of the BESS, the lower the resulting cost per kWh.

The safety of BESS installations and operations are always the top priority of all ship owners/operators. Ponant has shared its implementation of the 4.5 MWh BESS safety planning and procedures onboard LCC, including the energy storage room layout, ventilation, firefighting, and emergency plans in its public deliverable report D1.1 of NEMOSHIP [15]. The 4.5 MWh installation onto new LCC project was carried according to expectations with regard to safety, budget, and delivery time.

5.3. An unsuccessful attempt at retrofitting one BESS onto an older cruise ship

In contrast to the 4.5 MWh successful installation onto LCC, Ponant initiated a major retrofit of its first vessel LP, a 30-year-old 88-meter-long sailing motor cruise vessel in 2021. The intention was to integrate a BESS of 800 kWh to allow the ship to reach zero emissions at anchor or

Table 5
The key facts of the 500 kWh BESS retrofitting on NS.

Total installation cost	1.3 M€ (2616 €/kWh)	Received Norwegian government funding of 0.5 M€
Delivery time	6 months	From the initial order to completion of installation
BESS installation commissioning onboard	3 weeks	Including the sea trials and FMEA

Fig. 1. The 500 kWh BESS retrofitted onto NS in 2018.

Fig. 2. LCC in operation in ice and its 4.5 MWh battery room onboard.

Table 6
Key parameters of 4.5 MWh BESS installation on LCC.

Parameter	Value	Total and normalized values
Footprints	BESS room A plus converter & transformer room: 72 m^2 BESS room B plus converter & transformer room: 89 m^2	Total surface: 161 m^2 35 m^2/MWh
Weight	Total weight: 85 tons	19 kg/kWh
Costs	Battery purchasing costs: 3.8 M€ for 4520 kWh Transformer and converter costs: 962 k€ Installation costs: 150 k€. Including mechanical and electrical installation, and foundations Studies costs: 21.5 k€. Including studies and Class society fee	Total costs: 4.89 M€ 1100 €/kWh

alongside at pier through discharging of the batteries. Battery recharging was planned at sea during its transition mode.

Ponant conducted a Hazard Identification study for BESS integration on board the ship. The outcome of this research together with approval from the ship classification society Bureau Veritas (BV) has led to the purchase of a BESS. Apparently, the outcome of the HAZID together with the approval of BV was sufficient reason for Ponant to purchase an 800 kWh BESS in advance. Unfortunately, the submitted risk analysis and battery installation plans were rejected by the flag authorities, which stated that it was not safe to integrate the 800 kWh BESS on a 30-year old vessel, in a compartment below the waterline and in a narrow space. In the end, the purchased 800 kWh BESS could not be installed onto the vessel LP due to the lack of flag approval.

The unsuccessful retrofitting attempt onboard LP resulted from the fact that structured and transparent methodologies/tools were not available or at least not used to effectively support go/no-go decisions during the feasibility study. If the newly proposed installation go/no-go decision matrix in Section 4 was used, the show-stopping actions of the flag authorities which resulted in the no-go decision would have been identified as a risk at a very early stage. Accordingly, no 800 kWh BESS would have been purchased.

6. Operation analysis

Firstly, we delve into the operational outcomes of BESSs deployed on 47 OSVs under three different perspectives: (i) 18 OSVs from multiple ship owners/operators under Equinor's long-term contracts, (ii) 10 BESSs installed on OSVs operated by the experienced BESS ship operator Solstad, and (iii) 19 selected BESSs installed on OSVs monitored by the Corvus Lighthouse system. Secondly, the key operational insights gained from the 47 OSVs are summarised. Thirdly, the two-year operational results of the 4.5 MWh on a cruise ship were compared to the design targets.

6.1. BESS operations on 18 OSVs from multiple ship operators

Table 7 summaries the BESS data from 18 OSVs sourced from Maress including the total operational days, fuel efficiency, fuel saved, and the reduction of NO_x/CO_2. The fuel efficiency increase is the fuel consumption change compared to the baseline to measure the effectiveness of the battery installation. The battery actual EFC/designed EFC daily is extracted from the Corvus Lighthouse data system. The annual fuel savings per kWh of BESS installed are calculated by averaging the total fuel savings during the total operational years and dividing by rated kWh of BESS installed.

Table 7 shows that the installed BESS on 16 of the 18 OSVs achieved significant efficiency increases, fuel savings and NO_x/CO_2 reductions, and the other two batteries, Nr. 8 and 12, resulted in more fuel consumption instead of fuel savings. The greater fuel consumption might result from both lack of onshore power supply being used along with the losses experienced by the BESSs being larger than the measured fuel saving effects. The 16 vessels which achieved significant efficiency increases should have 40 % or above onshore power supply/charging avaibility according to the ship owners/operators' experiences. The different operational results in Table 7 also result from the different ship owners/operators which have different fuel-saving strategies and operational skills.

To quantify the relationship between battery sizes/usage and fuel savings, two new evaluation parameters (i) annual fuel saving kWh BESS installed and (ii) annual fuel saving kWh/EFC have been calculated. The calculated fuel savings per BESS kWh per year show that there is a large range from 79 to 899 kg/kWh yearly for the 16 OSVs that experienced positive fuel savings, with 625 kWh (No. 1) the lowest annual fuel saving of 79 kg/kWh and 568 kWh (No. 15) the highest of 899 kg/kWh. Also note that the large installed 875 kWh (No. 2 and No. 3) and 870 kWh (No. 16) BESSs resulted in lower annual fuel savings per kWh since these large BESSs have multi-objective operations, e.g., fuel saving and zero-emissions port (approaching port with only battery operation).

The 621 kWh on vessel No. 9 has the highest annual fuel savings per kWh BESS installed per EFC: 9.11 kg/kWh/EFC, giving the highest fuel savings with the minimum number of EFC.

Furthermore, the three BESSs with the same capacity (875 kWh) on three OSVs (No. 2, 3 and 4) result in very different levels of observed effectiveness: 88 kg/kWh, 241 kg/kWh and 488 kg/kWh annually. It is useful to note that the total fuel savings from Maress in Table 7 also include efforts such as the availability level of onshore power supply whilst at port, hull cleaning, propel washing and crew attitude towards energy efficiency and operational skills.

The EFC method is used as a metric of battery cyclic aging. Table 7 shows the EFCs of BESSs on 12 OSVs. 10 of the 12 BESSs have low actual EFCs compared to their designed EFCs and most of their EFCs are lower than 10 % of the designed EFC numbers. It is also noted that two vessels, nr. 2 and 11 have higher EFCs than the designed values. The low EFCs result from these BESSs being mainly used for spinning reserve power. The BESSs being used for spinning reserve power result in significant fuel savings with no or very low BESS charging/discharging cycle losses

Table 7
Overview of the effectiveness of the BESS installed on 18 OSVs.

Ship	Installed BESS capacity kWh	Days	Fuel efficiency increase %	Fuel saved Tons	NO$_x$ saved Tons	CO$_2$ saved Tons	Actual EFC/designed EFC daily	Annual fuel saving kg/kWh	Annual fuel saving kg/kWh/EFC
1	625	1737	2.77	236	7	755	0.1/5.6	79	2.17
2	875	1464	4.38	310	9	992	6.1/3.6	88	0.04
3	875	853	12.43	492	10	1147	–	241	–
4	875	1037	21.9	1212	32	3815	–	488	–
5	497	1829	12.76	1417	43	4544	0.6/4.7	569	2.60
6	565	672	2.25	89	3	284	0.3/2.8	86	0.79
7	621	1128	12.18	947	28	3036	0.5/7.44	493	2.70
8	746	1188	−3.47	−184	−6	−591	–	−76	–
9	621	1200	14.42	1019	1	2752	0.15/1.2	499	9.11
10	621	1341	19.36	1142	34	3661	0/1.2	501	–
11	621	1403	12.98	846	25	2711	4.8/1.2	354	0.20
12	746	1219	−3.41	−188	−6	−602	–	−75	–
13	621	1890	10.99	1070	32	3430	0.3/1.97	333	3.04
14	621	1890	7.62	781	23	2505	0.3/1.97	243	2.22
15	568	1798	24.8	2514	75	8060	–	899	–
16	870	456	15.24	301	9	965	–	277	–
17	621	1159	15.77	1600	48	5129	1.26/7.44	811	1.76
18	500	1857	13.7	1784	54	5718	0.59/4.5	706	3.3

(which results in low EFCs). These installed BESSs on the OSVs have the potential to be more actively used (e.g., have higher EFCs) to achieve additional benefits while still being within the designed number of EFCs (maintaining sufficient lifetime e.g., 10 years).

For vessel nr. 18 (NS), after 1857 days of operation, the total fuel saved is 1784 tons and CO$_2$/NO$_x$ reductions are 5718/54 tons respectively. The actual daily EFC divided by the designed daily EFC is 0.13 (0.59/4.5). The annual fuel savings per kWh BESS installed is 706 kg/kWh which shows that the fuel savings are highly effective due to the 500 kWh BESS installed. The annual fuel saving is 3.3 kg/kWh/EFC.

Table 8 and Fig. 3 show significant fuel consumption reductions during all four different operational modes (dynamic position (DP), Standby, Transition and Port). The large average fuel usage reduction reaches almost 50 % in Port, but it includes the use of onshore power supply. The fuel saving is mainly in DP operation and at Port if using onshore power supply. The fuel savings in other operational modes are limited for OSVs. However, the battery installation promotes the crew to have priority for energy efficient operations.

6.2. BESS operations on 10 OSVs by the same ship operator

Table 9 shows the operational results from 10 BESSs installed on 10 OSVs operated by the experienced BESS ship owner Solstad. The installed BESS capacity ranges from about 500 to 1000 kWh and the operational days of the BESS varied from 307 to 1857 days. Table 9 shows that all 10 ships have fuel efficiency increase during DP (no onshore power supply) which confirms the contributions provided by the installed BESS as spinning reserve capacity.

The smallest 500 kWh BESS on vessel No. 10 has the highest annual fuel savings per kWh BESS installed: 706 kg/kWh. The largest 996 kWh BESS on vessel No. 4 has relatively low annual fuel savings per kWh BESS installed: 295 kg/kWh. Larger BESS can be used to pursue new functions e.g., zero-emissions at port. The fuel savings in Table 9 include both the effects from both the BESSs and the use of onshore power supplies. For example, the 620 kWh BESS on vessel No. 9 has experienced very low fuel savings which might result from its low access to onshore power supply.

Table 8
Fuel consumption reductions during different operational modes onboard NS.

Ship	Change in DP tons/day	Change in standby tons/day	Change in transit tons/day	Change in port tons/day
Normand sun	−6.14 %	−12.59 %	−12.74 %	−47.83 %

6.3. Comparing BESS actual cycles vs. designed cycles onboard 19 OSVs

Corvus has compared the actual number of cycles experienced by BESSs against the designed number of cycles onboard 19 OSVs. The comparison is based on the following three conditions:

- Containerized BESS with a capacity varying from 452 kWh to 1424 kWh.
- Operational modes including DP, Transit and at Port.
- Only periods with quality lighthouse data (Corvus battery monitoring system).

The comparisons between the actual BESS cycles experienced vs. the originally designed cycles can be divided into seven clusters, according to the ship owners, as shown in Fig. 4 and Table 10.

The actual BESS cycles observed on the majority of OSVs (16 out of 19) are lower than the designed number of cycles. Six of the BESS even experienced a ratio of actual cycles vs. designed cycles lower than 10 %. This low number of actual cycles is consistent with the actual number of 80 cycles observed vs the designed number of 480 cycles annually (0.22 vs. 1.3 daily) from OMB6 project [13].

The EFC method provides a quick assessment on the intensity of battery usage. It is recommended to further develop the EFC method to include calendar aging and operational conditions and to validate EFC results using measurement data.

6.4. Key operational insights gained from 47 OSVs

The insights gained from the BESSs on 47 OSVs contribute to how to optimize the performance of marine BESSs, and are summarised as follows.

Firstly, the actual BESS operational results do not always show fuel savings. Table 7 shows, for BESS No. 8 and 12, an increase in fuel consumption instead of a fuel savings. The increase in fuel consumption may result from both lack of onshore power supply and the fact that the BESS losses are greater than the measured fuel savings effects. We should also keep in mind that the ship ages every year.

Secondly, the application of the EFC method reveals that the operational EFCs were notably lower than the designed EFCs. Further research is required to evaluate whether more benefits can be achieved by fully using the energy throughput of these BESSs.

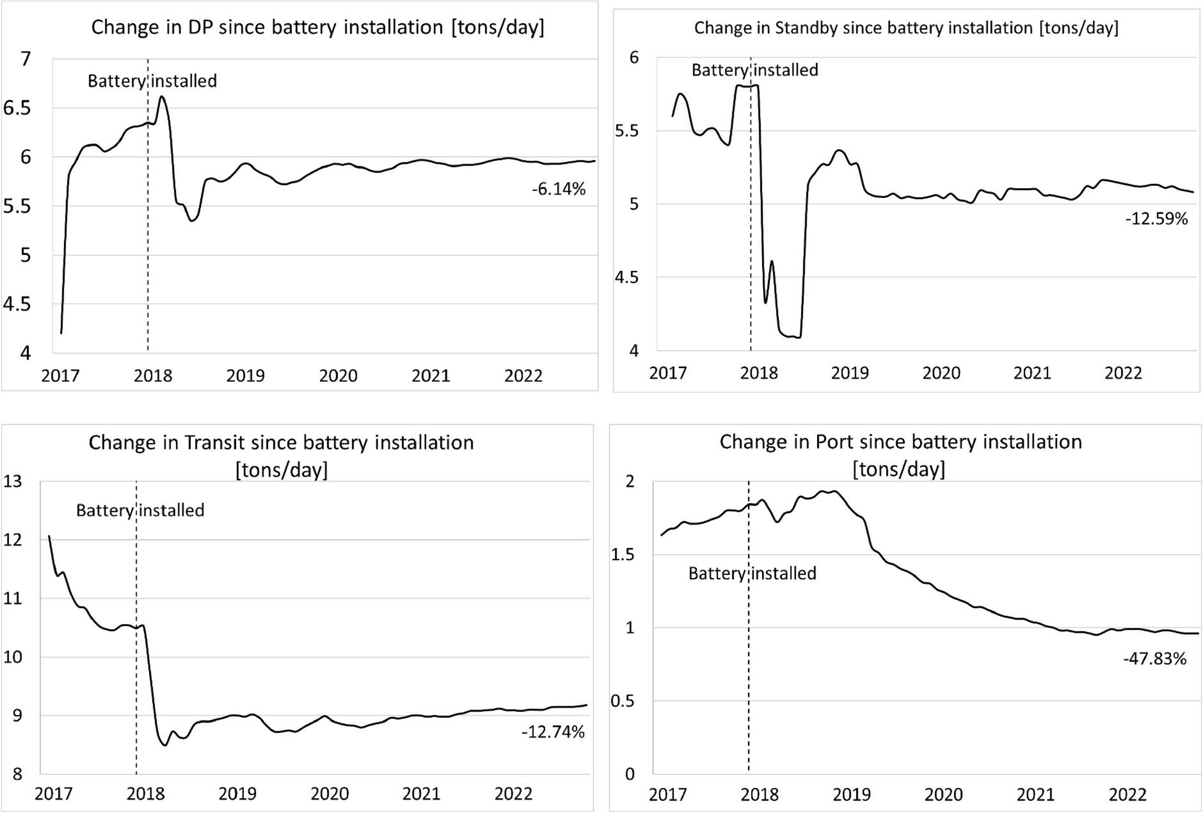


Fig. 3. Fuel consumption changes during DP, standby, transition and port modes on NS.

Table 9
An overview of effectiveness of the BESSs installed on 10 OSVs.

Ship	kWh	Days	Fuel efficiency increase %	DP fuel efficiency increase %	Fuel saved tons	NO_x saved tons	CO_2 saved Tons	Annual fuel saving per kWh kg/kWh
1	565	1067	12.44	15.06	607	18	1956	368
2	560	1553	10.48	12.03	950	29	3046	399
3	565	1067	11.16	7.35	537	16	1720	325
4	996	398	7.65	10.86	320	10	1026	295
5	500	1829	12.76	12.78	1417	43	4544	569
6	560	1494	15.11	10.02	1545	46	4953	674
7	745	307	7.8	16.03	154	5	494	246
8	560	1525	8.7	6.25	834	25	2674	356
9	620	672	2.25	5.66	89	3	283	78
10	500	1857	13.7	6.14	1784	54	5718	706

Thirdly, the proposed two new evaluation criteria effectively quantify the relationship between battery size/usage and fuel savings. For example, the evaluation criterion of the annual fuel savings per kWh battery shows that the same BESS installations on the same type of vessel can lead to very different effectiveness. This is illustrated in Table 7 which shows very different effectiveness levels for three similar BESSs with the same capacity (875 kWh) on three OSVs (No. 2, 3 and 4), namely 88 kg/kWh, 241 kg/kWh and 488 kg /kWh annually.

Fourthly, one learning is to optimize the operations at port level instead of only at vessel level. The availability level of onshore power supply and charging whilst at port has high impact on the fuel saving effectiveness from the installed BESSs.

Fifthly, the operation results in Table 7 also show lower annual fuel savings per kWh for several of the large BESSs. These lower fuel savings are due to the multi-objective operations of the BESSs, e.g., fuel saving and contribution to zero-emissions port (approaching a port with only battery operation). It is challenging to explore new optimal operations for larger capacity BESSs to meet multi-objective operations.

6.5. Operational results from the 4.5 MWh BESS installed on LCC

The 4.5 MWh BESS that was installed onto the newly built cruise ship LCC in 2021 shown in Fig. 2 has so far provided two years' worth of operational experiences and data. The BESS system consists of 40 packs connected in eight strings, where each string has five packs with its own inverter and two DC-DC converters. Each pack has capacity of 113 kWh. The BESS output power can reach a maximum of 5.5 MW due to the limitation of the power electronics (converters). The battery was dimensioned to initially deliver 60 min of zero emission operations with an average load of 3.31 MW for up to 400 cycles per year [19].

LCC does not have a reference vessel without batteries that could be used to measure the savings achieved. How to identify the most effective way to monitor battery use and to determine savings are future tasks to be completed during the NEMOSHIP project.

The fuel saving estimates for the different operational modes of the 4.5 MWh BESS on LCC are summarised in Table 11. Table 12 shows the gaps between the design objectives and the actual operational results.

Fig. 4. Comparison of the BESS actual usages vs designed usages on 19 OSVs.

The overall fuel-saving is estimated to be 1 to 2 % at this stage of analysis, which is lower than the designed objective for fuel savings of 5 %. Ponant and ABB Marine Norway jointly carried out tests onboard LCC to identify the low battery round trip efficiency on LCC in October 2022. The test results show the larger energy loss around 13 % is due to losses in the converters DC-DC and DC-AC, and batteries. Also the measured reactive power was flowing back and forth between the grid and the inverter through the transformer. One mitigation action is to use the generators to deliver most of the reactive power. Addressing these large losses necessitates further investigation.

7. BESS further development

This study recommends future research alignment with marine BESS

Table 10
A comparison of actual EFCs vs the designed FECs on 19 OSVs.

		Actual daily full cycle equivalents (ratio of the actual to designed)	Designed daily full cycle equivalents
Cluster 1 (ship owner 1): 4 vessels: 452 kWh	1	0.09 (20 %)	0.44
	2	0.03 (7 %)	0.44
	3	0.14 (32 %)	0.44
	4	0.04 (9 %)	0.44
Cluster 2 (ship owner 1): 2 vessels: 497 kWh	5	3.42 (113 %)	3.03
	6	9.68 (225 %)	3.79
Cluster 3 (ship owner 2): 2 vessels: 565/ 1424 kWh	7	0.80 (24 %)	3.27
	8	0.5 (8 %)	6.25
Cluster 4 (ship owner 3): 2 vessels: 621 kWh	9	0.31 (16 %)	1.97
	10	0.32 (16 %)	1.97
Cluster 5 (ship owner 4): 2 vessels: 678/ 994 kWh	11	0.3 (11 %)	2.8
	12	1.5 (18 %)	8.49
Cluster 6 (ship owner 5): 3 vessels: 621/ 994/994 kWh	13	0.35 (11 %)	3.28
	14	0.27 (3 %)	8.49
	15	0.6 (7 %)	8.49
Cluster 7 (various ship owner): 4 vessels: from 525 to 870 kWh	16	2.35 (24 %)	9.81
	17	0.69 (10 %)	6.85
	18	4.64 (129 %)	3.6
	19	0.13 (2 %)	5.6

Table 11
Fuel saving estimates for different operational modes of 4.5 MWh BESS on LCC.

Operations	Frequency	Saving
Manoeuvring	2 %	9.50 % (spinning reserving)
Port/anchor	20 %	0 to 5 % to be evaluated with dedicated software
Ice navigation	16 %	0 % (peak shaving mode)
Transit	62 %	0 to 5 % to be verified (stabilizing the electric grid frequency)
Total	100 %	Overall: 1 to 2 % fuel saving at this stage of analysis.

Table 12
Operational benefits from operating a 4.5 MWh BESS on LCC.

	Design objectives	Actual operational results
Fuel saving	5 % of fuel saving was expected and a ROI of 10 years	1–2 %
Operational safety	Secure the vessel operations by preventing black out and stabilizing the grid frequency, optimizing the use of dual fuel engines running on gas mode	Not measurable
GHG emission reduction	Improving the engine load and reducing fuel consumption and methane slip emissions	BESS contributes to less GHG emissions due to less fuel saving
Losses measurement	The round-trip efficiency: around 90 %	Total losses: around 15 %

further development including enhancing safety measurements, exploring on/offshore power supply and charging, optimizing multi-objective operations, and progressing towards zero emissions.

Firstly, there are increasing safety requirements for the installation and operation of BESS onboard all types of vessels. The ship owner and the system integrator aim to standardize interfaces (including mechanical, electrical power, telecommunications and thermal connections) between the vessels and BESS retrofitting or installing. To mitigate the increasing safety risks, risk management should be enhanced, e.g., documenting the experiences learned whilst preparing for the changes required by newer safety requirements, including extending BESS integration onboard to both onshore green power supply and charging infrastructure and preparing for new risks (such as cyber-attacks). It is recommended to continue to update safety training programs to build up the long-term skills needed by the crew to follow/support safe electrification of ships.

Corvus has addressed R&D needs for modularity and standardization of BESS to support increasing safety requirements in six aspects: (i) emergency management, (ii) continuous improvement, (iii) in-house competence, (iv) continuous monitoring, (v) quality control and (vi) information sharing.

Secondly, the onshore power supply and charging significantly increase the fuel-saving benefits from the installed BESSs on vessels. The future offshore power supply and charging are expected to have higher fuel-saving impact than the onshore power supply and charging since the load at offshore site (e.g., DP) is significantly (10–100 times) higher than the hotel loads at Port. BESS operational strategies must extend beyond vessel level and also incorporate port level to fully utilize the advantages of onshore/offshore power supply and charging.

Thirdly, it is challenging to explore new optimal operations for larger capacity BESSs to meet multi-objective operations, e.g., meeting new environmental regulations and pursuing maximum annual fuel savings per kWh. There is a strong need to develop practical methods that can handle these multiple objectives.

Finally, to progress towards further lower/zero emissions, new operational strategies and training of crew are required to unlock the potential of BESSs with larger capacity, or a greater number of individual BESS units installed onto hybrid OSVs. With the future available offshore power supply and charging facilities, the required BESS capacity on offshore ships will be optimized, enabling the construction of more fully electric ships. More specifically, the full electric OSVs for offshore wind farms might be achieved in the near future. Another alternative is that the BESS combines with the low-emission marine fuel to progress towards zero emissions.

In summary, this industry-driven study has provided comprehensive lessons learned from the commercial exploitation of more than 750 marine BESSs. It also examined what additional R&D efforts are needed to enable shipowners/operators to kick-off faster or install more BESSs on their vessels.

CRediT authorship contribution statement

Wei He: Writing – original draft. **Lars O. Valøen:** Writing – original draft. **Kjetil V. Olsen:** Writing – original draft. **Kåre M. Kjeka:** Writing – review & editing. **Bjørn M. Fredriksen:** Writing – review & editing. **Mathieu Petiteau:** Writing – original draft. **Amine Touat:** Writing – original draft. **Helge Såtendal:** Writing – review & editing. **Aaron Howie:** Writing – original draft. **David Howey:** Writing – review & editing. **Rambabu Kandepu:** Writing – review & editing. **Carsten F. Hammershøj:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

All authors thank the NEMOSHIP consortium's support and contribution to this paper writing. Special thanks to Guénaël Le Solliec (CEA) and Solène Goy (CEA), Pilar Meneses (CIDETEC), Cristi Irimia (Siemens) and Calin Husar (Siemens) and Erdeniz Erol (Elkon) for reviewing the paper, discussions of digital platform and BESS integration on vessels. All authors thank Harold Dijk (DNV) and Prof. Egbert Figgemeier (RWTH) for their critical questions and important improvement suggestions during the paper writing.

Funding

The NEMOSHIP project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No 101096324. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority. Neither the European Union nor the granting authority can be held responsible for them.

Disclaimer

This paper presents BESSs on vessels study for NEMOSHIP project and does not represent in any way author's company strategies or views of BESS development.

References

[1] EU policy, strategy and legislation for 2030 environmental, energy and climate targets, available online: https://commission.europa.eu/energy-climate-change-environment/overall-targets-and-reporting/2030-targets_en, (accessed 11 February 2024).

[2] DNV, Available online: https://www.dnv.com/about/sustainability/index.html. (Accessed 11 February 2024).

[3] K. Kim, K. Park, J. Ahn, G. Roh, K. Chun, A study on applicability of Battery Energy Storage System (BESS) for electric propulsion ships, in: IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), June 2016, pp. 203–207.

[4] S. Fang, Y. Xu, Z. Li, T. Zhao, H. Wang, Two-step multi-objective management of hybrid energy storage system in all-electric ship microgrids, IEEE Trans. Veh. Technol. 68 (4) (2019) 3361–3373.

[5] M. Huang, W. He, A. Incecik, A. Cichon, G. Królczyk, Z. Li, Renewable energy storage and sustainable design of hybrid energy powered ships: a case study, J. Energy Storage 43 (2021) 103266.

[6] T.J. McCoy, Electric ships past, present, and future [technology leaders], IEEE Electrification Mag. 3 (2) (2015) 4–11.

[7] H. Daniel, J.P.F. Trovão, D. Williams, Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier, eTransportation 11 (2022) 100150.

[8] He, W.; Såtendal, H.; Byklum, E.; Wikborg, A, Equinor ASA, The OFFSHORE ENERGY SUPPLY SYSTEM, The patent cooperations treaty (PCT) WO 2023/219515 A1 on 16 November 2023.

[9] C. Ünlübayir, U.H. Mierendorff, M.F. Börner, K.L. Quade, A. Blömeke, F. Ringbeck, D.U. Sauer, A data-driven approach to ship energy management: incorporating automated tracking system data and weather information, J. Mar. Sci. Eng. 11 (2023) 2259, https://doi.org/10.3390/jmse11122259.

[10] G. Lucà Trombetta, S.G. Leonardi, D. Aloisio, L. Andaloro, F. Sergi, Lithium-ion batteries on board: a review on their integration for enabling the energy transition in shipping industry, Energies 17 (2024) 1019, https://doi.org/10.3390/en17051019.

[11] Int. https://www.sdir.no/en/shipping/legislation/directives/battery-fire-with-subsequent-gas-explosion/. (Accessed 6 April 2023).

[12] Battery-powered excursion vessel overheats in Norway, sparking fear of explosion. gcaptain.com. (Accessed 6 April 2023).

[13] W. He, O. Mo, A. Remøy, L.O. Valøen, H. Såtendal, A. Howie, P.J.S. Vie, Accelerating efficient installation and optimization of battery energy storage system operations onboard vessels, Energies 15 (2022) 4908. https://www.mdpi.com/1996-1073/15/13/4908. (Accessed 22 May 2023).

[14] OMB6 (Optimizing Marine Battery Operations Using 6 Years' Operational Data from Two Commercially Operating Vessels). Available online: https://www.sintef.no/en/projects/2021/omb6-optimizing-marine-battery-operations/ (accessed on 16 May 2022).

[15] NEMOSHIP (New electrical architecture and digital platform for optimising large battery systems on ships), Horizon-Cl5-2022-D5-01-01, https://cordis.europa.eu/project/id/101096324 (assessed on 22 May 2023).

[16] Yxney Marime, Maress systems. https://www.inmarsat.com/en/apps/maritime/yxney.html (assessed on 22 May 2023).

[17] Marorka Online reference guide (February 2018). https://online.gtt.digital/Account/LogOn (assessed on 10 July 2023).

[18] Corvus Lighthouse. https://corvusenergy.com/services/digital-solutions/(assessed on 22 May 2023).

[19] Corvus Battery System Specification of “Le Commandant Charcot” – Ref. 5202-13-FEB-2018.