Lessons learnt from high impact R&D projects from ZEWT and other sectors with ESS

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Abstract—The objective of this paper is to cluster the main challenges and gaps for the safe integration of batteries in vessels, and for the improvement of the operation and performance of energy storage in the maritime sector. To do this, a benchmarking methodology was developed that compares technical and non-technical topics relevant to the identification and classification of EU-funded R&D projects with NEMOSHIP project. Firstly, the most relevant projects were selected considering the main topics of NEMOSHIP and their relationship with waterborne, electromobility, stationary or energy storage applications in general. Secondly, a weighting criterion is established for each project by evaluating the information available for each topic. In addition, the different technological trends, decisions, and roadmaps established in the most relevant and selected projects of the methodology are analysed. Finally, general conclusions and a compilation of lessons learned are presented from both a technical and nontechnical perspective.

Keywords—Battery vessel integration, cloud services, CO_2 emissions reduction, digital tool, ESS hybridisation, maritime sector.

1. Introduction

The primary goal of the NEMOSHIP initiative is to extend zero-emission capabilities within the maritime sector while prioritizing safety and standardising integration processes. The design of a modular battery system for hybrid vessels, ensuring optimal and safe utilization, and showcasing their readiness and adaptability for fully electric ships is a novelty in maritime R&D projects. We estimate that these innovations will contribute by 2030 to the electrification of about 7% of the European fleet and a 30% reduction in EU maritime emissions. These efforts encompass enhancements in the environmental sustainability of marine engines, ensuring safer operations, and the implementation of innovative solutions.

This paper aims to analyse the background of past EUfunded projects aiming to identify risks, mitigation strategies, challenges, and insights gained from the development of the innovative vessel electrification projects. Furthermore, it examines various technology trends, decisions, and roadmaps established in the projects.

Section II outlines a methodology for identifying projects most relevant to NEMOSHIP in terms of lessons learned, decisions made and electrification strategies. Then a benchmarking of these projects is presented. Section III provides a summary of the most relevant projects for NEMOSHIP in the maritime sector, focusing on technology, integration, challenges, gaps, etc.; projects integrating hybrid storage system also known as heterogenous storage; it summarizes the technical and non-technical lessons learned from the review of evaluated projects; and concludes with the ongoing activity in parallel to NEMOSHIP project. Finally, Section IV presents the conclusions drawn.

2. Benchmarking methodology

2.1. Comprehensive search for H2020 and HEU projects

First, a project search was carried out. In the Waterborne Technology Platform [1] project of interest for NEMOSHIP were reviewed. Then, the search was performed in TRIMIS, Transport Research and Innovation Monitoring and Information System [2], via the Search Hub, by filtering "projects" type of content, Waterborne transport mode and start date of 2017 or later. Additionally, projects not related to NEMOSHIP were discarded. As a result, an initial list of 68 projects was obtained.

Secondly, a commercial platform, WHEESBEE [3], was used to complement the list of projects. It has the advantage of including R&D projects financed by the European Commission, as well as by national governments from several countries of Europe, USA, Canada, and Australia. In this case, the search was not restricted to the maritime field since some topics are better covered in other sectors. The most relevant projects have been selected considering key topics such as digital twins/models, EMS/BMS, and/or ESS integration in the vehicle/site.

Finally, the list consisted of 80 CORDIS projects and 447 projects funded by national governments. The focus was put on CORDIS projects given the ease of access of information.

2.2. Projects selection by topics and additional criteria

To identify the most useful projects for the analysis of lessons learned, a benchmarking methodology was employed, comparing both technical and non-technical aspects across various topics (Table 1). The aim was to determine the extent to which NEMOSHIP-related topics were addressed or developed within each project, assigning one point for each covered topic. However, it can be challenging to see if the topic has been addressed since there is sometimes limited information available about the project, that is why half points were also included.

Table 1 - Technical and non-technical topics relevant to nemoship project

Technical topics	Non-Technical topics
T1 = Digital Twin tools	NT1 = Training activities
T2 = EMS/BMS	NT2 = Dissemination activities
T3 = ESS integration	NT3 = LCA & environmental
T4 = ESS hybridisation	NT4 = Stakeholder interaction
T5 = Cloud services	NT5 = R&D gaps
T6 = Predictive maintenance	NT6 = New standards/regulation
	NT7 = Socio-economic barriers

Table 2 - Technical analysis of selected EU-funded R&D projects

Sector	Acronym	T1	T2	T3	T4	T5	T6	Weight
Waterborne transport	CURRENT DIRECT	🟢	🟢	🟢	🟢	🟢	🔴	5
	E-FERRY	🔴	🟢	🟢	🔴	🟢	🔴	3
	NAUTILUS	🟢	🟢	🟢	🟢	🔴	🔴	4
	SEABAT	🔴	🟢	🟢	🟢	🔴	🔴	3
	JOULES	🟢	🔴	🟢	🟢	🔴	🔴	3
	DT4GS	🟢	🔴	🔴	🔴	🟢	🟡	2,5
	MAGPIE	🟢	🟡	🟡	🔴	🟡	🔴	2,5
	AUXILIA	🔴	🔴	🟢	🟢	🔴	🔴	2
	Ghost boat	🔴	🔴	🟢	🔴	🔴	🔴	1
	HYSEAS III	🔴	🟢	🟢	🟢	🔴	🔴	3
	Sea Li-ion	🔴	🟢	🟢	🔴	🔴	🔴	2
	ENDURUNS	🟡	🟢	🟢	🟢	🔴	🔴	3,5
	RENship	🔴	🔴	🟢	🟢	🔴	🔴	2
	MARANDA	🟡	🟢	🟢	🟢	🔴	🔴	3,5
	HYPOBATT	🟢	🟢	🔴	🔴	🔴	🔴	2
	ACCEL BARGE	🔴	🔴	🟢	🔴	🔴	🔴	1
	CHEK	🟢	🔴	🟢	🟢	🔴	🔴	3
	AENEAS	🟢	🟢	🟢	🟢	🔴	🔴	4
	TrAM	🟢	🔴	🟢	🔴	🔴	🔴	2
	NAVAIS	🟡	🔴	🔴	🔴	🔴	🔴	0,5
	VESSELAI	🟢	🔴	🔴	🔴	🟢	🔴	2
e-Mobility	ORCA	🟢	🟢	🟢	🟢	🔴	🔴	4
	NextETRUCK	🟢	🟢	🟢	🔴	🟢	🟢	5
	TWAICE	🟢	🟢	🔴	🔴	🟢	🟢	4
	BATTERY PLUS I	🟡	🟢	🟡	🔴	🔴	🟢	3
Aeronautics	AKSELOS INTEGRA	🟢	🔴	🔴	🔴	🔴	🟢	2
	Battery check	🔴	🔴	🟢	🔴	🟢	🟢	3
	AEGIS	🟡	🔴	🟢	🟢	🔴	🔴	2,5
Stationary	LOLABAT	🔴	🟢	🟢	🔴	🔴	🔴	2
	HEROES	🔴	🔴	🟢	🟢	🟢	🟡	3,5
	iSTORMY	🟢	🟢	🟢	🟢	🔴	🟡	4,5
	HYBRIS	🟢	🟢	🟢	🟢	🟢	🟡	5,5
	SCORES	🔴	🟢	🟢	🟢	🔴	🔴	3
General-multisector	NENUFAR GAM-2020-SYS	🔴	🟢	🟢	🔴	🔴	🟡	2,5
	FUTPRINT50	🟢	🟢	🟢	🟢	🔴	🔴	4
	ESTEEM	🟡	🟢	🟢	🔴	🔴	🔴	2,5
	OPENSRUM	🔴	🟢	🟡	🔴	🟡	🟢	3

Blue = Selected projects / Grey = Discarded projects for additional reasons
🟢 = 1 = Topic is covered in the projects / 🔴 = 0 = Topic is not considered in the project
🟡 = 0,5 = Topic seems to be addressed but there is not much information, or it is not specifically covered

Initially, technical topics were assessed (see Table 2), in which the last column of the table indicates the weight assigned to each project based on the technical topics covered. Regarding waterborne projects, a threshold weight of 3 was defined, as it is the most relevant sector for NEMOSHIP. For the other sectors, the threshold was fixed to 4. Projects above the thresholds are highlighted in blue; project highlighted in grey were discarded as they have different context, or limited information available or are just very recent projects.
Finally, the most relevant and interesting projects for extracting the key challenges and lessons learnt (see section 4) for NEMOSHIP are:

- Maritime domain: E-FERRY, NAUTILUS, MARANDA, JOULES, LASTING, COLUMBUS, SEABAT and Current Direct
- Road mobility: ORCA
- Stationary applications: HYBRIS and iSTORMY
- Multi-sector project: FUTPRINT50

COLUMBUS and LASTING, which are waterborne projects, were added for non-technical reasons. In Table 3, results of the non-technical topics evaluation are displayed. From here we can also extract the conclusion of which nontechnical activities are the most recurrent. Dissemination activities are very often carried out (in 76 % of the evaluated projects), but training activities and contribution to new standard/regulations are the least covered (only 27 % of the projects).

Table 3 - Non-technical analysis of selected EU-funded R&D projects

Sector	Acronym	NT1	NT2	NT3	NT4	NT5	NT6	NT7
Waterborne transport	CURRENT DIRECT	🔴	🟢	🔴	🟡	🟡	🟢	🟡
	E-FERRY	🟢	🟢	🟢	🟢	🟢	🔴	🟢
	NAUTILUS	🔴	🟢	🟢	🟡	🟢	🔴	🟢
	SEABAT	🔴	🟢	🔴	🔴	🟢	🟢	🔴
	COLUMBUS	🟢	🟢	🔴	🟡	🟢	🔴	🟢
	LASTING	🟢	🟢	🔴	🟡	🟢	🔴	🟡
	JOULES	🔴	🟢	🟢	🔴	🟢	🟢	🟢
	DT4GS	🟢	🟢	🔴	🟢	🟡	🟢	🔴
	MAGPIE	🟢	🟢	🔴	🟢	🟡	🟡	🟢
	AUXILIA	🔴	🔴	🔴	🔴	🟡	🔴	🔴
	Ghost boat	🔴	🔴	🔴	🟢	🟡	🔴	🟢
	HYSEAS III	🟢	🟢	🟢	🟢	🟡	🟡	🔴
	Sea Li-ion	🔴	🟢	🟢	🟡	🟢	🟡	🔴
	ENDURUNS	🔴	🟢	🟢	🔴	🟢	🔴	🟢
	RENship	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	MARANDA	🔴	🟢	🟢	🟢	🟡	🔴	🔴
	HYPOBATT	🟢	🟢	🔴	🟢	🟢	🟢	🔴
	ACCEL BARGE	🔴	🟢	🟡	🟢	🔴	🔴	🟢
	CHEK	🟡	🟢	🟢	🟡	🔴	🔴	🔴
	AENEAS	🔴	🟢	🟢	🔴	🟡	🔴	🔴
	TrAM	🔴	🟢	🔴	🔴	🔴	🔴	🔴
	NAVAIS	🔴	🟢	🟡	🟢	🟢	🟢	🟢
	VESSELAI	🔴	🟢	🔴	🟢	🟡	🔴	🔴
e-Mobility	ORCA	🔴	🟢	🔴	🔴	🔴	🔴	🔴
	NextETRUCK	🔴	🟢	🔴	🔴	🔴	🔴	🔴
	TWAICE	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	BATTERY PLUS I	🔴	🟢	🔴	🔴	🔴	🔴	🔴
Aeronautics	AKSELOS INTEGRA	🔴	🔴	🔴	🔴	🔴	🔴	🟢
	Battery check	🔴	🔴	🟡	🔴	🔴	🔴	🔴
	AEGIS	🔴	🟢	🔴	🟢	🔴	🟢	🟢
Stationary	LOLABAT	🔴	🟡	🟢	🟡	🟢	🔴	🟢
	HEROES	🔴	🟢	🔴	🟢	🔴	🔴	🟢
	iSTORMY	🔴	🟢	🟢	🔴	🟡	🔴	🔴
	HYBRIS	🟢	🟢	🟢	🔴	🟡	🟡	🟢
	SCORES	🟢	🟢	🟢	🟢	🔴	🟡	🟡
General-multisector	NENUFAR GAM-2020-SYS	🔴	🔴	🟡	🔴	🔴	🔴	🔴
	FUTPRINT50	🟢	🟢	🔴	🔴	🟢	🟢	🔴
	ESTEEM	🔴	🔴	🔴	🔴	🔴	🔴	🔴
	OPENSRUM	🔴	🔴	🔴	🔴	🔴	🔴	🔴
Non-technical topic evaluation		**10,5** (26.9 %)	**29,5** (75.6 %)	**15** (38.5 %)	**16,5** (42.3 %)	**17,5** (44.9 %)	**10,5** (26.9 %)	**15,5** (39.7 %)

Blue = Selected projects
🟢 = 1 = Topic is covered in the projects / 🔴 = 0 = Topic is not considered in the project
🟡 = 0,5 = Topic seems to be addressed but there is not much information, or it is not specifically covered

3. COLLECTION OF LESSONS LEARNED FROM RESEARCH AND INNOVATION PROJECTS

3.1. Summary of maritime domain projects

E-FERRY [4] is a project which involves: 1) fully electric powered 'green' ferry demonstration that can sail between island communities, coastal zones, and inland waterways in Europe and beyond without polluting and CO_2 emissions; 2) efficient design and building combining lightweight equipment and materials; and 3) validation of the feasibility and cost effectiveness.

- *Cloud service development:* An automatic system for the collection and processing of minutely recorded data from navigation, alarms, PMS and auxiliary systems has been developed. Different data is later accessible depending on the user type.
- *ESS integration in the vessel:* A 4 MW peak charge and 4.3 MWh of capacity Li-ion battery system was integrated in two separate battery rooms; each of the rooms consisting of 10 separate strings of batteries, at a nominal capacity of 215 kWh each. The battery technology relies on specific NMCtype cells manufactured by project partner Leclanché GmbH. DC-based distribution for battery charging allows each power source to be utilised individually and optimally.
- *BMS/EMS development:* Cells are monitored at a string level by the Leclanché BMS. The BMS communicates with the global PMS developed by Danfoss via CAN protocol. Functionalities such as cyclic counting health monitoring are integrated in the PMS. Battery balancing, on the contrary, is automatically performed at night by both.

The **NAUTILUS [5]** project aims at developing, evaluating, and validating a highly efficient power generation system fuelled by Liquefied Natural Gas (LNG) with a further reduction of GHG and onboard emission by replacing conventional engines with hybrid Solid Oxide Fuel Cell (SOFC)-battery gensets.

- *ESS hybridisation:* The project proposes a hybrid genset that combines SOFC system of 10x100 kW and a 1x300 kW battery. To face limitations of space and weight, as well as dynamic performance, a modular system is proposed which is initially composed of a 1.3 MW hybrid genset, and 35 MW internal combustion engine (ICE). It reaches a 50 % electrical efficiency, up to 77 % with heat recovery. A further step on this is the balanced hybridisation where a 50 % hybrid genset and 50 % ICE is conceptualised. The last step would be the full hybrid genset implementation.
- *ESS integration in the vessel:* A 60-kW functional demonstrator was integrated in the existing vessel. The proposed system is modular so that the 5 to 60 MW conceptualised system can be easily built in based on modular hybrid genset units of 100 to 250 kW.
- *EMS/BMS development:* The Energy Management Unit is the system in charge of the power split for continuous supply, near-optimal fuel consumption and reduce degradation. For that, the hybrid genset composed of SOFC and battery handles the transient load supply. As a result, the battery is maintained at an intermediate level of SOC (~50 %). The Battery Management Unit enables the interface between the battery and the hybrid genset control.

MARANDA [6] project, develops an emission-free hydrogen fuelled based hybrid powertrain system for marine applications.

- *ESS hybridisation:* The 165 kW (2 x 82.5 kW AC) fuel cell powertrain hybridised with a battery will provide power to the vessel electrical equipment as well as the dynamic positioning. Fuel cell feeds the network with power, but the battery system is the one maintaining the voltage and frequency. The PMS oversees optimisation, and lower-level Fuel Cell System control follows its orders. In load transient the emergency storage is activated for the slope of fuel cells to be lower.

The EU-funded **JOULES [7]** project aims to reduce carbon dioxide and all other emissions of European-built ships; develop predictive tools using advanced simulation models of the energy grid of the ship; and identify operating profile conditions to provide additional potential to increase the overall energy efficiency of ships.

- *ESS integration in the vessel:* Use of different energy storage technologies was considered, to be paired with renewable energy sources like solar PV. Different energy storage technologies were modelled including flywheels, ultracapacitors and different battery chemistries. This has been helpful to understand the best ways to utilise different components in terms of sizing, safety, and control requirements, and develop a smart power management.

The EU-funded **LASTING [8]** project does not focus on technical aspects but on finding methods to increase the engagement of the waterborne transport sector in R&D activities. In this project some challenges and gaps regarding dissemination, research and development have been identified: i) there is information available on technical aspects, but not much on the economics and business models related to technical innovations, ii) more and better structured information on technology/innovation from EU RD&I projects is needed, iii) information not always reached the right audience, etc.

COLUMBUS [9] project intends to capitalise on the significant investment of the European Commission in marine research by ensuring accessibility and uptake of research knowledge outputs by end-users, ensuring measurable value creation from research investments. Specific knowledge acquisition and transfer methodologies are proposed. Multiple training activities were carried out in, i) developing impact plans, ii) funding opportunities for knowledge transfer initiatives, or even iii) stakeholders' identification and engagement. Some R&D gaps were also identified, as science-policy communication to be improved, or significant industrial barriers for technology innovation. As for socioeconomic barriers, lack of skilled workforce or lack of free and open-access data were noticed.

SEABAT [10] project objective is to develop a fullelectric hybrid concept based on combining modular highenergy (HE) and high-power (HP) batteries. On the one hand, component costs will be reduced by using low-cost modular components being also suitable for future high-power battery generations. On the other hand, it will reduce oversizing, total cost of ownership of maritime batteries and their footprint.
Regarding number of cycles, most marine battery systems have a design life of 10 years. This results in 300 to 1000 cycles per year, or 0.8 to 2.7 cycles per day, for LFP and NMC batteries. However, in case of LTO batteries, is reflected as 2500 cycles per year, or 6.8 per day.
Battery powered vessels were analysed based on their operations, making a difference between primary and secondary cycles. Primary cycles are the main cycles expected from operational conditions at design level, e.g. a ferry travelling between two ports. The secondary cycles refer to operations performed outside of the average behaviour due to environmental conditions, emergencies or specific battery services such as load levelling and spinning reserve. Cycles were classified from C-Rate and number of cycle point of view. As for the C-rate, 80% of the primary cycles have a Crate below 6, while the 80% of secondary cycles have a C-rate requirement below 3C. This is mainly due to the lower energy needed for primary cycles, with similar power required for both.
The project also provides some HESS concept design recommendations. HESS is recommended to be rack- or traybased, with racks being the most stable, and trays having the highest performance. Regarding safety, cell level thermal runaway propagation and gas exhaust ducting is suggested.

Table 4 - Recommendations for hess concept design [10]

	HE BESS	HP BESS
System cost	400 €/kWh	510 €/kWh
Cycle cost	0.07 €/kWh	0.04 €/kWh
Energy density	180 Wh/Kg, 270 Wh/L	90 Wh/Kg, 120 Wh/L
Power density	280 Wh/Kg, 400 W/l	700 Wh/Kg, 1000 W/l
Cycle lifetime	16000 @80% DOD	5000 @80% DOD
Output voltage	700-1000 Vdc	
Heat rejection	0.5-1.5 % of discharge power @1C	
Cooling	~25ºC inlet	

For fire extinguishing, a water mist system is the most effective. The BMS should handle unlimited parallel strings and should not exceed 0.63 W/kWh of consumption. Redundancy is also recommended, and active balancing with at least 7.5 mV accuracy. Therefore, each cell needs at least one voltage sensor, and one temperature sensor per four cells. More recommendations are summarised in Table 4.
In case of the HESS architecture selection, it was decided to integrate a low-voltage DC-DC converter for every battery module, considering total cost of ownership and scalability on all domains. This allows to place the units in series to achieve a controlled DC voltage and in parallel lines to scale total HESS energy capacity.

Current Direct [11] EU-funded project is developing a swappable battery energy storage container that operates on an Energy-as-a-Service (EaaS) platform. It will also integrate a distributed BMS, referred to as a Single Cell Supervisor (SCS). The EaaS platform will include a physics-based battery model, and the container standardised interfaces for both onshore and vessel operations.
The swappable battery energy storage enables easier integration and is not constrained by the available space. It will be installed in a standard ISO 20-foot equivalent mobile container up to 1 MWh. It also includes a frequency converter for DC-AC conversion and a transformer for AC voltage adequation. As supporting function to this main equipment, HVAC, telematics, control voltage, fire- and gas detection and fire mitigation means are needed. For charging, these containers will be moved to dedicated charging stations on the shore side by means of cranes between the shore and the vessel.
With a fixed installation, the electrical connections to the vessel electrical infrastructure are well defined and easy to implement. Cooling is typically managed by linking the deck house to the vessel's cooling system, while fire protection is extended from the vessel's standard fire mitigation systems.

In Current Direct, a cloud based EaaS platform is being developed to create a system which supplies electric vessels by swapping their depleted batteries with fully charged batteries in store and charge their depleted batteries locally with optimised charging operations. It consists of a control unit for logistic optimisation, and a web platform for monitoring. The control unit optimises the transfer of energy from the batteries (when to recharge/reserve the batteries), and the management of the battery fleet and stations. The aim is to ensure that end users have the energy they need, when they need it, at a competitive price.

Table 5 - Hybridisation projects comparison

PROJECT	To be reduced	Heterogeneous storage
AENEAS	Fuel consumption	SC + SSB
NAUTILUS	Emissions	SOFC + BESS
SEABAT	ESS degradation	HP BESS + HE BESS
MARANDA	Emissions	FC + BESS
AUXILIA	Fuel consumption	FESS + BESS
HYSEAS III	Emissions	SOFC + BESS
ENDURUNS	Cost	SOFC + BESS (submarine)
CHECK	Emissions	FC + BESS (+ wind turbines)

SC = Supercapacitor, SSB = Solid State Battery, SOFC = Solid Oxide Fuel Cell, HP = Highpower, HE = High-energy, FC = Fuel Cell, BESS = Battery ESS, FESS = Flywheel ESS.

3.2. Hybridisation projects

ESS hybridisation can be understood in two different ways. On the one side, as ESS hybridized with additional power sources as genset or renewable energies. On the other side, if only storage system is considered, heterogenous concept is used to refer to a storage system composed of different technologies. Therefore, in NEMOSHIP project the aim is to integrate a heterogeneous system.

Focusing on this, a comparison of used technologies for heterogeneous storage systems was developed. For that, previously discarded projects were included since they cover the hybridisation topic more deeply, which are AENEAS [12], AUXILIA [13], HYSEAS III [14], ENDURUNS [15], and CHECK [16].

Tab. 3. highlights the diverse use of energy storage technologies across various projects aimed at reducing emissions, fuel consumption, ESS degradation, or costs. Projects focusing on emissions, NAUTILUS, MARANDA, HYSEAS III and CHECK, employ a combination of fuel cells and battery storage systems, underscoring the importance of clean energy solutions. In contrast, projects targeting fuel consumption, like AENEAS and AUXILIA, use different technologies such as supercapacitors, solid-state batteries, and flywheel systems, demonstrating the flexibility of storage options based on specific project goals. In addition, the integration of both high power and high energy battery systems, as seen in SEABAT, reflects the possibility of optimised sizing with tailored energy management to improve performance and reduce degradation. Moreover, ENDURUNS makes profit of fuel cells and battery storage systems, in this case for cost reduction.

3.3. Lessons learnt

At the beginning of the project, it is important to identify constraints related to operating conditions, installation requirements and safety issues. Figure 1 summarizes the technical conclusions and lessons learnt.

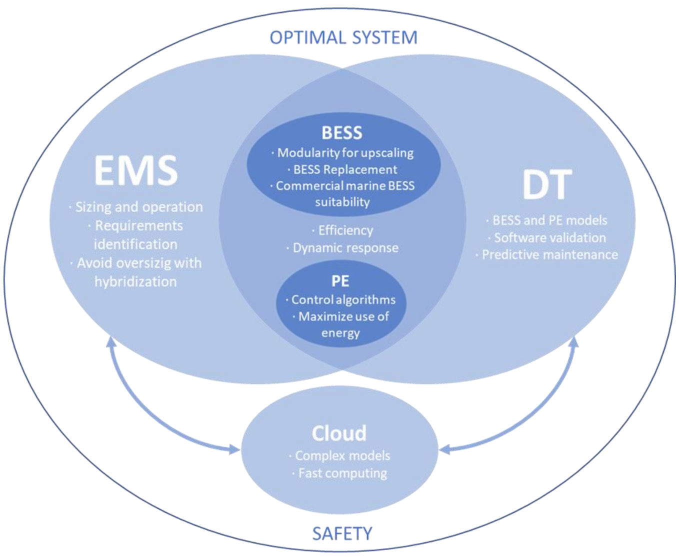

Figure 1 - Summary of conclusions and leassons learnt

Regarding the **EMS,** not only depends on operation conditions, but also on the sizing, which can even be optimized for specific strategies avoiding oversizing.

- Control algorithms need to be developed for innovative systems to guarantee power supply as well as optimising fuel consumption and asset lifetime. Algorithms may be specific for each vessel or application (NAUTILUS).
- Ship operators must respect several operational, economic and maritime criteria while permitting the reduction of fuel consumption. Since this could suppose a complex task, decision making should rely on software (JOULES).
- Aggregating monitoring data of different local BMSs, better storage system state estimation is achieved (HYBRIS).
- Different tasks can support and **optimal operation**:
- Energy grid optimisation could improve the environmental performance by up to 20 % (JOULES).
- The power sharing between high-power and highenergy storage systems can be optimised to control and shift the high-frequency and high-slope currents in terms of lifetime improvement (ORCA).
- Weight and space constraints are key aspects to be optimised in future designs (NAUTILUS).
- Volumetric power density and increased overall genset efficiency are key parameters to be optimised in future low emission vessels with limited space (NAUTILUS).
- C-Rate optimization could be interesting for hybrid system (SEABAT).
- Power split for continuous demand supply, enables near-optimal fuel consumption and reduce degradation (NAUTILUS).

In **cloud programming**, it is also important for optimal computational system, data collection and store:

- The collection and processing of multiple signals, measurements and parameters can be done by the cloud system since it can communicate with the different elements of the vessel and build an on-line database (E-FERRY).
- Process communication interfaces which will define the operation of the system must be properly selected (HYBRIS).
- An advanced BMS implemented in a server in the cloud will benefit from more computational resources with the possibility to further develop complex models (HYBRIS).
- In relation to the **BESS marine market**, the lessons learnt are these:
- LFP cells are selected for the HE battery pack, and NMC cells are considered for the HP battery pack (iSTORMY).
- 2nd-life batteries are not viable now due to relatively high cost and limited market maturity (iSTORMY).
- Nowadays, ESS technologies for marine applications available in the market are not optimal for operational requirements of the ships (SEABAT).

In terms of **hybridisation**, the lessons learnt are these:

- Hybridisation gives the ability to cover all necessary requirements, avoiding oversizing (MARANDA).
- Battery size and costs can be reduced while maintaining performance, extending battery life, and improving operational range in terms of offered services, storage time, peak energy, or even working temperature (HYBRIS).
- Differences in operations conditions of the hybridised technologies need to be considered for power electronics selection and location (NAUTILUS).
- Important and challenging to find optimum combination of choice of sustainable fuel and onboard ship technologies to reach cost effective GHG reductions (JOULES).

In the case of **power electronics** analysis, this will also be important when ESS is hybridised since control algorithm should be effectively integrated with an accurate coordination of the use of different technologies. It is also important from the efficiency point of view to maximise the use of energy and reduce possible energy losses. When building digital twin tools, together with the model of the ESS, the power electronics is also modelled, since it is where the control algorithm is implemented. Therefore, complex models are necessary, even more if technologies are hybridised.
Lessons learnt regarding **upscaling and construction** are provided below:

- In a real full electric vessel, two replacements of ESS are expected over its life span. This is something to consider in the economic analysis, as well as in the modularity and ease of replaceability of the BESS (E-FERRY).
- Modularity is a key feature when trying to scale functional prototypes to multi-MW systems (E-FERRY and NAUTILUS).
- Combining vessel automation and power management in a single system, reduces the number of the external connections (MARANDA).
- Containerised HESS is easy to transport, considering prototype dimensions. (HYBRIS)

When including an ESS in a vessel, additional **safety measures** need to be included. ESS can pose a risk if the battery usage limits are not respected, or even if the necessary operating conditions are not maintained. Considering that ESS integration in vessels is still not a common resource, failures are expected to happen until the technology becomes mature. Therefore, safety measures are important.

The main **key challenges** identified are: 1) educational requirement for future ferry crews, 2) sophisticated electrical charging infrastructure, 3) viable volumetric density due to weight and space constraints, 4) optimal hybrid sizing, 4) cost competitiveness, 5) available marine battery systems not fitting the operation requirements.

4. Clustering activities

The knowledge acquired in all the summarized projects is useful for the development of new projects such as NEMOSHIP. But also, sharing knowledge and results between ongoing European projects contributes to maximise impact among others. NEMOSHIP has been in contact for clustering activities, with a number of ongoing projects, most of which are funded under ZEWT (Zero Emission Waterborne Transport) call topics. Details of these recent projects are provided in Table 6.

ZEWT is a Partnership in the framework of Horizon Europe. The aim of the Partnership is to "provide and demonstrate zero-emission solutions for all main ship types and services before 2030, which will enable zero-emission waterborne transport before 2050" [17]. The first Horizon Europe calls for proposals in the framework of that Partnership took place in June 2021. Some of the abovementioned projects are part of the European Waterborne Transport Synergy Ecosystem (EU WT-SE) which was launched by project FLEXSHIP in collaboration with HYPOBATT and SEABAT. EUWT-SE scope is to share research strategies, broadening the reach beyond each consortium, by actively partnering with other relevant EU-funded projects. The initiative was set up in November 2023 and now counts seven projects looking forward to further leveraging common results: FLEXSHIP, SEABAT, HYPOBATT, AENEAS, NEMOSHIP, DT4GS and BlueBARGE. The projects below cover several domains of the maritime sector decarbonation and electrification: from technology (e.g. novel energy storage systems), and design (e.g. modular electrical architecture, heterogeneous/hybrid systems, digital twins/advanced modelling) to operations (e.g. charging systems, control algorithms) incl. demonstration of innovations within real vessels for the higher TRL projects.

Table 6 - Clustering activities / selection of ongoing projects

PROJECT	Title/Keywords
NEMOSHIP (IA) CEA, France 01/23 - 12/26	New modular Electrical architecture and digital platforM to Optimise large battery systems on SHIPs https://cordis.europa.eu/project/id/101096324
	Keywords: Electric architecture, modularity, battery usage optimisation, heterogeneous storage systems, digital twins.
SEABAT (RIA) Flanders Make, Belgium 01/20 – 12/24	Solutions for largE bAtteries for waterBorne transport https://cordis.europa.eu/project/id/963560
	Keywords: Sustainable transport, electrochemistry, batteries and fuel cells, electric propulsion, hybrid battery system, scalable and modular battery architecture.
FLEXSHIP (IA) BRING, Belgium 01/23 - 12/26	Flexible and modular large battery systems for safe onboard integration and operation of electric power, demonstrated in multiple type of ships https://cordis.europa.eu/project/id/101095863
	Keywords: Electrification of vessel fleets, KPIs for offshore electrification, ships' PMS optimization, marine DC grids, modular BESS, marine digital twin, lesson learnt for vessel fleet re/electrification, e-vessel crews training and education, waterborne digitalization, ships retrofitting.
HYPOBATT (IA) IKERLAN, Spain 06/22 - 11/25	HYper POwered vessel BATTery charging system https://cordis.europa.eu/project/id/101056853
	Keywords: Electrification, electrified ships, multi-MWcharging, fast charging, CO-reduction, standardization, modularity.
DT4GS (RIA) INLECOM Group, Belgium 06/22 - 05/25	Open collaboration and open Digital Twin infrastructure for Green Smart Shipping https://cordis.europa.eu/project/id/101056799
	Keywords: Digital twins, green smart shipping, decarbonisation, shipping dataspace.
AENEAS (RIA) Flanders Make, Belgium 02/23 - 01/26	innovAtive ENErgy storage systems onboArd vesselS https://cordis.europa.eu/project/id/101095902
	Keywords: Solid state batteries, supercapacitors, HIL simulation, digital twin, battery LCA, electrified waterborne transport.
BlueBARGE (IA) ABS, Greece 01/24 - 12/26	Blue Bunkering of Anchored ships with Renewable Generated Electricity https://cordis.europa.eu/project/id/101138694
	Keywords: Power bunkering, cold ironing, onshore power supply, offshore power supply, electrification, ships power supply, power barge.

V-ACCESS (RIA) University of Trieste, Italy 02/23 - 01/26	Vessel Advanced Clustered and Coordinated Energy Storage Systems https://cordis.europa.eu/project/id/101096831	
	Keywords: Supercapacitors, superconducting magnetic energy storage, shipboard power systems, hazard identification and analysis, system integration.	
POSEIDON (RIA) Centro Tecnológico Naval y Del Mar, Spain 01/23 - 12/26	POwer StoragE In D OceaN https://cordis.europa.eu/project/id/101096457	
	Keywords: Supercapacitors, flywheels, superconducting magnetic energy storage (SMES), lifecycle analysis (LCA), LCC (Life Cycle Cost) Analysis, HAZID, system integration.	

5. Conclusions

As a conclusion, this paper summarises the lessons learnt collected from different EU projects which covers some technical topics to be addressed in NEMOSHIP project. Optimizing storage size was shown to be an important task for a vessel and this can also be supported by the PMS where usage of the storage system is maximized. Power electronics together with modularity play a key role in hybridised systems and cloud programming enables the integration of complex systems. This and other more innovative concepts are being addressed in other recent EU projects. All the knowledge developed and to be developed will support the improvement of the operation and performance of energy storage in the maritime sector, contributing to the electrification of vessels.

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