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NEMOSHIP

NEW **MO**DULAR ELECTRICAL ARCHITECTURE AND DIGITAL PLATFORM TO OPTIMISE LARGE BATTERY SYSTEMS ON **SHIP**S SHIPS

GRANT AGREEMENT No. 101096324

D1.2: Lessons learnt from ZEWT projects and from other sectors

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Project summary

The ambition of the NEMOSHIP project is to develop, test and demonstrate new innovative technologies, methodologies and guidelines to better optimise large electric battery power technology within hybrid and fully electrically powered ships. The project will act as a key enabler of the new co-programmed European Partnership Zero Emission Waterborne Transport (ZEWT) roadmap to better reach International Maritime Organization (IMO) objectives regarding the reduction of Greenhouse Gas (GHG) emissions from waterborne transport by 2030 and 2050.

To help achieve this ambition, NEMOSHIP will develop a modular and standardised battery energy storage solution that is able to exploit heterogeneous storage units and a cloud-based digital platform to enable data-driven, optimised, and safe exploitation. The project will demonstrate the maturity of these innovations at TRL 7 for hybrid ships as well as their adaptability towards fully electric ships thanks to the observations collected from a retrofitted hybrid Offshore Service Vessel (OSV) (diesel/electric propulsion), a newly designed hybrid cruise vessel (LNG/electric propulsion) and a semi-virtual demonstration of two additional fully electric vessels employed in tasks such as ferrying and short-sea shipping.

The NEMOSHIP consortium estimates these innovations will contribute by 2030 to the electrification of about 7% of the European fleet and the reduction by 30% of EU maritime GHG emissions compared to business-as-usual scenario.

The NEMOSHIP consortium is composed of 11 partners (3 RTO, 1 SME, 7 large companies) and covers the whole value chain, from research-oriented partners to software developers, energy system designers, integration partners, naval architects, and end-users.

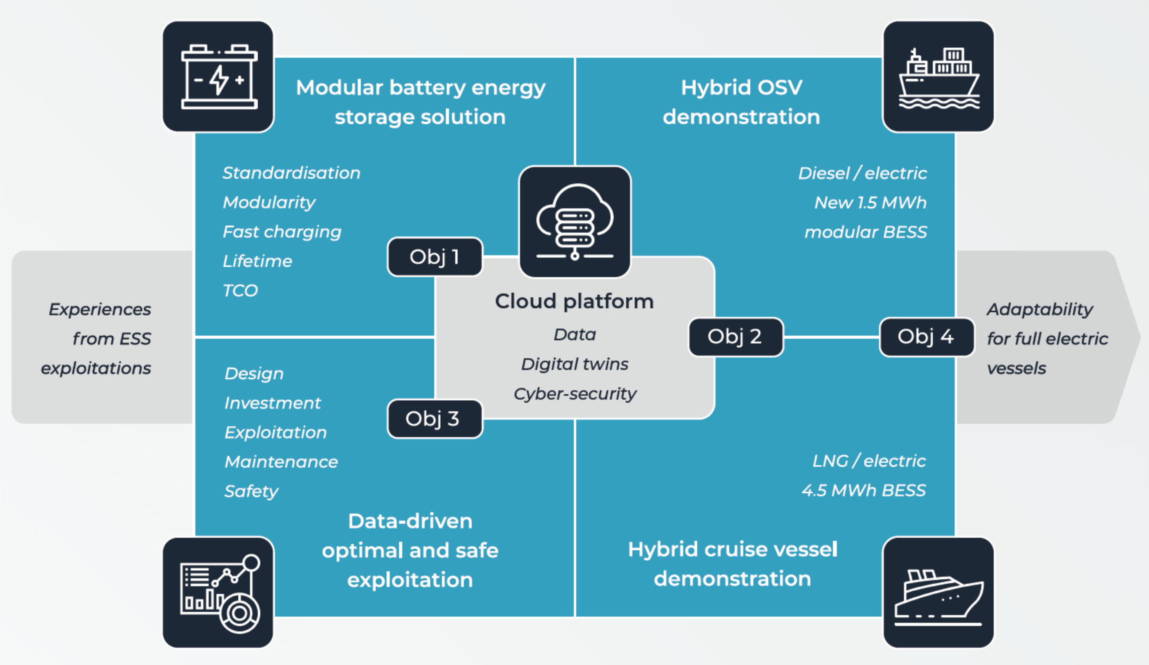


Figure 1 – NEMOSHIP objectives at a glance

Report overview

The aim of this deliverable is to collect, report and cluster the main challenges, gaps, lessons learnt from previous EU research projects related to the integration of batteries in different applications to provide inputs for the development and implementation of the NEMOSHIP project. Additionally, the different technology trends, decisions and roadmaps established in the different projects are analysed.

Inputs collected are derived from public information available for H2020 and Horizon Europe (HEU) projects in the mobility sector (maritime, road, etc.) and for stationary applications. Moreover, the present report goes deeper in two recent Horizon Europe projects, SEABAT and CURRENT DIRECT, which are considered more relevant to NEMOSHIP scope.

The overall aim of the report is to take these inputs into consideration for the safe integration of batteries in vessels and for improvement of operation and performance of the energy storage in the maritime sector.

Table of content

1 Introduction

Research is looking into new and better waterborne transport concepts to encourage moving freight by water rather than road as part of the energy transition framework. These include improving the environmental performance of marine engines, safer operations and deploying research and innovative solutions. New frontiers in vessels and the industrial use of the oceans need to be explored further.

The main objective of NEMOSHIP is to extend zero emissions for the maritime sector in a safe way, achieving standardisation in the integration process. Another objective is related to the development of a cloud-based digital platform and advanced tools for ship operators enabling data-driven exploitation.

Overall, NEMOSHIP project seeks to develop a modular battery energy storage solution in hybrid vessels, with optimal and safe exploitation and demonstrate their maturity as well as their adaptability for full-electric ships.

The aim of this report is to analyse the background of projects previously funded under the H2020 and HEU programmes, in order to identify risks, mitigations schemes, challenges and learnings from the development of these innovative projects for vessels electrification. Additionally, the different technology trends, decisions and roadmaps established in the different projects are analysed.

Firstly, in section 2, a methodology to identify the projects the most relevant to NEMOSHIP scope in terms of lessons learnt, decisions and electrification roadmaps was defined based on 3 steps; a final benchmarking is presented in that section.

Then, section 3 summarises the most relevant projects for NEMOSHIP in terms of technology, integration, challenges, gaps and learnings, as well as other non-technical issues.

In section 4, a focus is made on two projects from the LC-BAT-11-2020 call, SEABAT and CURRENT DIRECT.

And finally section 5 concludes the report with a summary of the technical and non-technical lesson learnt from this project review.

2 Methodology

The main goal of this task is to identify relevant projects in the field of maritime transport electrification, as well as projects related to energy storage systems (ESS) in other sector such as road mobility and stationary applications.

The below technical and non-technical topics were considered relevant for NEMOSHIP project:

Technical topics:

T1 = Digital Twin tools
T2 = EMS/BMS
T3 = ESS integration
T4 = ESS hybridisation
T5 = Cloud services
T6 = AI-based predictive maintenance

Non-technical topics:

NT1 = Training activities
NT2 = Dissemination activities
NT3 = LCA & environmental issue analysis
NT4 = Focus on stakeholder interaction
NT5 = R&D gap definition
NT6 = Contribution to new standard/regulations
NT7 = Socio-economic barrier identification

The methodology followed, which is based on identification and classification of projects relevant for NEMOSHIP, is described below.

2.1 Comprehensive search for H2020 and HEU projects

As a first step, a project search was carried out on two specific transport websites:

- Waterborne Technology Platform - https://www.waterborne.eu/projects
- Transport Research and Innovation Monitoring and Information System (TRIMIS) - https://trimis.ec.europa.eu/

After reviewing the projects of interest for NEMOSHIP in the Waterborne Technology Platform, the search was performed in TRIMIS. This website is organized in 7 sections, each one corresponding to a priority area of the European Strategic Transport Research and Innovation Agenda (STRIA):

- Transport electrification (ELT)
- Vehicle design and manufacturing (VDM)
- Transport infrastructure (INF)
- Connected and automated transport (CAT)
- Smart mobility and services (SMO)
- Network and traffic management systems (NTM)
- Low-emission alternative energy for transport (ALT)

All content provided by TRIMIS (events, programs, etc.) is categorised under one or more STRIA priorities. TRIMIS offers a Search Hub (https://trimis.ec.europa.eu/search) to look for content and provide useful filters to refine searches. For this purpose, “projects” type of content was selected and two additional filters were specified:

- Transport mode: Waterborne
- Start date: 2017 or later (to look for the most recent developments and to narrow down the vast number of results). Note: one project which started before 2017 was taken into account based on its relevance to NEMOSHIP scope (E-FERRY project).

Among the 562 projects obtained, 429 were discarded as not related to NEMOSHIP project (for example, those related to noise impact, ship hull, wave models, natural gas propulsion, etc.). Therefore, an initial list of 68 projects was selected. The more relevant to NEMOSHIP objectives fell under the category of ELT, as expected, and some of them also addressed other categories such as ALT, VDM or INF.

It was verified that all the projects of interest identified through the Waterborne Technology Platform were also included in TRIMIS.

In a second step, a commercial platform, WHEESBEE, was used to complement the list of projects obtained in the first step (TRIMIS has not included yet the projects which started in 2022). WHEESBEE was chosen since it provides R&D data (projects, patents, publications, etc.) from different sources and 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 and from USA, Canada, and Australia.

A broad query was performed to obtain projects starting from 2017 related to the use of batteries for maritime transport electrification, by combining the keywords battery and at least one of the followings: waterborne, vessel, ship or maritime. As a result, a list of 240 projects was obtained.

In addition, a set of queries was performed to address the main goals of NEMOSHIP:

- Digital twins/models
- EMS/BMS
- ESS integration in the vehicle/site
- ESS hybridisation
- Services in the cloud
- Training activities for ESS operation
- Predictive maintenance (AI based)

For this purpose, the search was not restricted to the maritime field since some topics are better covered in other transport sectors such as the automotive sector. Queries with different combinations of keywords related to the mentioned goals were thus performed.

Finally, 527 projects were gathered as a result from WHEESBEE search (with a project starting date from 2017): 80 CORDIS projects and 447 projects funded by national governments (Australia, Belgium, Finland, France, Italy, Norway, Portugal, the Netherlands, United Kingdom, and USA).

The focus was put on CORDIS projects given the ease of access to information about these (e.g. language-wise) and because the current work focuses on European projects. Nevertheless, if available in English, abstracts of projects not funded under an EU scheme were also reviewed (e.g., regional/national projects), to be up to date with R&D efforts. These projects will be briefly mentioned in Appendix B.

2.2 Initial selection by topics

Following the comprehensive search described in Section 2.1, a more detailed selection was made in section 2.2. In this filtering step, the most relevant projects have been selected taking into account both the topics mentioned above or their relation to either waterborne, electromobility, stationary or general battery/energy storage applications (Table 1).

Table 1 – List of H2020 and HEU projects to be analysed

Sector	Acronym	Project title	Project coordinator
Waterborne transport	**CURRENT DIRECT**	CURRENT DIRECT – Swappable Container Waterborne Transport Battery	Vrije Universiteit Brussel (BE)
	E-FERRY	E-FERRY – Prototype and full-scale demonstration of next generation 100% electrically powered ferry for passengers and vehicles	Aero Kommune (DK)
	NAUTILUS	Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships	Deutsches Zentrum Fur Luft - Und Raumfahrt Ev (DE)
	SEABAT	Solutions for largE bAtteries for waterBorne trAnsporT	Flanders Make (BE)
	COLUMBUS	COLUMBUS - Monitoring, Managing and Transferring Marine and Maritime Knowledge for Sustainable Blue Growth	Bord Iascaigh Mhara (IE)
	LASTING	Let's go for waterborne transport research - broadening engagement and increasing impact	Shipyards and Maritime Equipment Association of Europe (BE)
	JOULES	Joint Operation for Ultra Low Emission Shipping	Flensburger Schiffbau-gesellschaft Mbh & Co KG (DE)
	DT4GS	Open collaboration and open Digital Twin infrastructure for Green Smart Shipping	Inlecom Group (BE)
	MAGPIE	sMArt Green Ports as Integrated Efficient multimodal hubs	Havenbedrijf Rotterdam NV (NL)
	AUXILIA	Hybrid Drive for Commercial Ships and Yachts	R.T.N. (IT)
	Ghost boat	A new way to own, drive and maintain a boat	D&A Experiences Oy (FI)
	HYSEAS III	Realising the world's first sea-going hydrogen-powered RoPax ferry and a business model for European islands	The University Court of the University of St Andrews (UK)
	Sea Li-ion	Sea Li-Ion	Stena Rederi Ab (SE)
	ENDURUNS	Development and demonstration of a long-endurance sea surveying autonomous unmanned vehicle with gliding capability powered by hydrogen fuel cell	Altus Lsa Commercial and Manufacturing SA (GR)
	RENship	Hybrid Carbon-free electrically driven fishing longliner with low power methanol combustion engine for propulsion back-up and auxiliary equipment	Navis Ehf (IS)
	MARANDA	Marine application of a new fuel cell powertrain validated in demanding arctic conditions	Teknologian Tutkimuskeskus Vtt Oy (FI)
	HYPOBATT	Hyper powered vessel battery charging system	Ikerlan S. Coop (ES)
	ACCEL BARGE	Accelerated Electrification of Inland Waterways	E-portliner Holding B.V. (NL)
	CHEK	deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs	University of Vaasa (FI)
	AENEAS	Advanced European Network of E-infrastructures for Astronomy with the SKA	Flanders Make (BE)
	TrAM	Transport: Advanced and Modular	Rogaland Fylkeskommune (NO)
	NAVAIS	New, Advanced and Value-Added Innovative Ships	Stichting Netherlands Maritime Technology Foundation (NL)
	VESSELAI	Enabling maritime digitalization by extreme-scale analytics, AI and digital twins	Ethnicon Metsovion Polytechnion (GR)

e-Mobility	**ORCA**	Optimised Real-world Cost-Competitive Modular Hybrid Architecture for Heavy Duty Vehicles	TNO (NL)
	NextETRUCK	Efficient and affordable Zero Emission logistics through NEXT generation Electric TRUCKs	TNO (NL)
	TWAICE	TWAICE predictive analytics and digital twin ecosystem to optimise and automate batteries second life and re-use	Twaice Technologies Gmbh (DE)
	BATTERY PLUS I	High performing batteries for accelerated uptake of hybrid and electric vehicles	Millor Energy Solutions Sl (ES)
Aeronautics	**AKSELOS INTEGRA**	Disruptive Digital Twin solution combining sensor data streams and high accuracy physics-based models to design and monitor large structural assets	Akselos SA (SE)
	Battery check	Take the mystery out of battery life	Batterycheck S.R.O. (CZ)
	AEGIS	Advanced efficient and green intermodal systems	Sintef Ocean As (NO)
Stationary	**LOLABAT**	Long LAsting BATtery	CY Cergy Paris Universite (FR)
	HEROES	Hybrid EneRgy stOragE Stations	Beyonder As (NO)
	iSTORMY	Interoperable, modular and Smart hybrid energy STORage systeM for stationarY applications	Vrije Universiteit Brussel (BE)
	HYBRIS	Hybrid Battery energy stoRage system for advanced grid and beHInd-de-meter Segments	Idp (ES)
	SCORES	Self Consumption Of Renewable Energy by hybrid Storage systems	Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek Tno (NL)
General-multisector	**NENUFAR GAM-2020-SYS**	Next gEneration of eNergy storagE solUtions For more electricAl aiRcrafts	CEA (FR)
	FUTPRINT50	Future propulsion and integration: towards a hybrid-electric 50-seat regional aircraft	University of Stuttgart (DE)
	ESTEEM	Advanced Energy STorage and Regeneration System for Enhanced Energy Management	The University of Nottingham (UK)
	OPENSRUM	Optimal Power Conversion and Energy Storage System for Safe and Reliable Urban Air Mobility	Vaalborg Universitet (DK)

2.3 Final selection by topics and additional criteria

In order to select the most relevant projects for the lessons learnt analysis, a benchmarking methodology which compares technical and non-technical aspects by topics was implemented.

After the identification of useful projects for the compilation of lessons learnt, an approach to evaluate the different projects and selecting the most relevant ones was defined. The idea was to identify which of the NEMOSHIP topics were considered or developed in the projects, giving one point for each topic covered. However, it can be challenging to see if the topic has been addressed since there is sometimes limited information available about the project. There are some projects that do not have their own website detailing their activities and results. When a topic seems to be addressed but limited information was available about it, the approach developed allowed half points.

First, technical topics were evaluated and results are summarised in Table 2. The last column shows the weight of each project considering the technical topics addressed. 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 based on the reasons described below the table.

Table 2 – Technical analysis of selected H2020 and HEU 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
	FUTPRINT5O	🟢	🟢	🟢	🟢	🔴	🔴	4
	ESTEEM	🟡	🟢	🟢	🔴	🔴	🔴	2,5
	OPENSRUM	🔴	🟢	🟡	🔴	🟡	🟢	3

Blue = Selected projects / Grey = Discarded projects for additional reasons (see below)
🟢 = 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 limited information, or it is not specifically covered

- **HYSEAS III:** Different context/application (hydrogen related project, fuel cell ESS).
- **ENDURUNS:** Different context/application (submarine and hydrogen related project, fuel cell ESS).
- **CHEK:** Limited information available.

- **AENEAS:** Started recently (in 2023), limited lessons learnt might be extracted.
- **NextETRUCK:** Started recently (in 2022), limited lessons learnt might be extracted.
- **TWAICE:** No ESS integration, more software related project, and limited information available.

Additionally, COLUMBUS and LASTING, which are waterborne projects, were added for non-technical reasons. In Table 3, results of the non-technical evaluation are displayed. The analysis shows which non-technical aspect is the most worked on in the European projects selected. Among the selected projects, dissemination activities are very often carried out (in 76 % of the evaluated projects), but training activities and contribution to new standard/regulations are more rarely covered (only 27 % of the projects).

Table 3 – Non-technical analysis of selected H2020 and HEU 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** (27 %)	**29,5** (76 %)	**15** (39 %)	**16,5** (42%)	**17,5** (45 %)	**10,5** (27 %)	**15,5** (40 %)

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 limited information, or it is not specifically covered

3 Summary of relevant projects

This section details the relevant NEMOSHIP-related topics included in the selected project, along with the key challenges extracted and/or lessons learnt. In particular, E-FERRY, NAUTILUS, MARANDA, JOULES, LASTING and COLUMBUS among the waterborne projects, ORCA for road mobility, HYBRIS and iSTORMY which are stationary application projects, and in addition FUTPRINT50 which is a more generalist multi-sector project.

The SEABAT and CURRENT DIRECT projects are further analysed in the next section (Section 0).

3.1 Regional projects

The aim of this task is to analyse projects previously funded under the H2020 and HEU programmes. Nevertheless, some regional projects were also evaluated and those selected are listed in Table 4. The term regional refers here to projects that are not funded by H2020 or HEU but that may involve partners from several countries.

Table 4 – List of regional projects identified

Project	Country	Start & end
1. Battery Digital Twins	UK	2022 - 2023
2. Hybrid Battery Optimisation	UK	2019 - 2021
3. An Advanced Battery Energy Storage Control System for Predictive Maintenance	UK	2020 - 2021
4. The Conversion of The UK's First Domestic Passenger Vessel to Fully Electric Propulsion	UK	2020 - 2022
5. Zero Emission Systems for Ship Propulsion	UK	2021 - 2023
6. Hybridisation of Fishing Vessel Propulsion	NL	2020 - X
7. Green Sailing	NL	2017 - X
8. Low Energy Battery Management System for The Maritime Sector	NL	2018 - X
9. INTENS Hypro	NL	2017 - 2020
10. Electrical Solutions for Enabling Zero Emission Ferries	NO	2017 - 2018
11. New Energy Storage System	NO	2017 - 2022
12. Dtyard - Digital Twin Yard	NO	2019 - 2022
13. Zeff - Zero Emission Fast Ferry	NO	2018 - 2021

14. Optimising Marine Battery Operations Using 6 Years Operational Data from Commercially Operating Vessels	NO	2021 - 2026
15. Opthymob - Optimised Hydrogen Powered Maritime Mobility	NO	2022 - 2025
16. Zelag	IT	2017 - 2018
17. Port Liner	NL	2017 - X
18. Less	IT	2017 - 2018
19. INSYDE-PRO-SHIPS - Study of Insulating Systems Design and Verification Processed for Shipboard Integrated Power Systems	IT	2018 - 2019
20. PIEZO - Plug-In Electric Zero-Emission Offshore-Ship	NO	2020 - 2023

Table 5 shows the number of the above projects which address a NEMOSHIP-related topic. The focus is on ESS integration and hybridisation, followed by development of EMS or BMS strategies.

Table 5 – Evaluation of NEMOSHIP related topics addressed in the regional projects

Services in the cloud	Digital twins	Predictive maintenance	ESS integration	ESS hybridization	EMS/BMS
0	2	4	9	9	8

3.2 Waterborne projects

In the following sections, the EU projects selected in Section 2 are detailed, highlighting the most relevant aspects related to NEMOSHIP.

3.2.1 E-FERRY

Start date: June 2015

End date: May 2020

Type of project: H2020 research and innovation program under grant agreement N° 636027

Project coordinator: Hellenic Institute of Transport (GR)

Summary: E-FERRY is a project which involves the design, building and demonstration of a fully electric powered 'green' ferry that can sail without polluting and CO_2 emissions. It promotes energy efficient, zero GHG emission and air pollution free waterborne transportation for island communities, coastal zones and inland waterways in Europe and beyond.

Main objectives:

- Build an innovative vessel combining energy efficient design, lightweight equipment, materials, and state-of-the-art electric only systems with automated high power charging system as a cost-efficient alternative to fossil-fuelled ferries.
- Validate and prove the feasibility and cost effectiveness of the concept to the industry and ferry operators by demonstrating an energy efficient and emission free ferry for passengers and vehicles in an operational viable setup on the Soeby-Fynshav and Soeby-Faaborg connections in the Danish part of the Baltic Sea.
- Obtain life cycle assessments taking this innovative concept into consideration to ensure that the right design choices are made for ferries lasting 30 years into the future. Life cycle assessments

also will take into account the CO_2, NO_x and SO_2 emissions and energy consumption involved in manufacturing and transporting the parts for manufacturing the E-FERRY.
- Obtain approval of the use of carbon fibre reinforced (CFR) composite modules in the E-ferry’s superstructure according to SOLAS Chapter II-2 (Part F) regulation 17 and EU Directive 2002/25/EC through material and fire testing using guidelines from the KOMPAS-project. All findings from the approval process of CFR composite modules for the E-FERRY design will be made available for the European maritime industry through the project dissemination and exploitation activities.
- Reduce CO_2 emissions by approx. 2,000 tonnes, NOx by 41,500 kg, SO_2 by 1,350 kg and particulates by 2,500 kg per year from 2017 when the demonstration ferry is put into operation.
- Quantify the potential market up-take and CO_2-reductions on European scale and qualify the potential application of the concept on a larger scale among relevant industry and ferry operators.
- Develop a business case/model and prepare the concept for market uptake starting soon after the end of the demonstration E-FERRY project.

Topics related to NEMOSHIP goals:

Technical topics: EMS/BMS, ESS integration in the vessel/vehicle/site, services in the cloud.

Project website: http://e-ferryproject.eu/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: cloud services development, ESS integration in the vessel and BMS/EMS development.

Cloud services development

In the E-FERRY project an automatic system for data collection and processing has been developed which name is Valment DNA Integrated Automation System (IAS). The IAS communicates with key ferry elements like the navigation and alarm systems, the Power Management System (PMS) and other auxiliary systems via TCP/IP protocols as shown in Figure 2. Different types of data are collected via the E-FERRY IAS, i.e. technical data like energy consumption, charging data or power usage but also navigational data like position, speed or rate of turn.

These data are continuously logged in the IAS, and subsequently extracted manually, via the Valmet DNA program, into an excel sheet, where values for each of the parameters are provided per minute. The database is password protected and allows for different types of users to get different types of access to the data. The on-line database allows users to specify dates, time intervals (within limits) and parameters that they want to investigate.

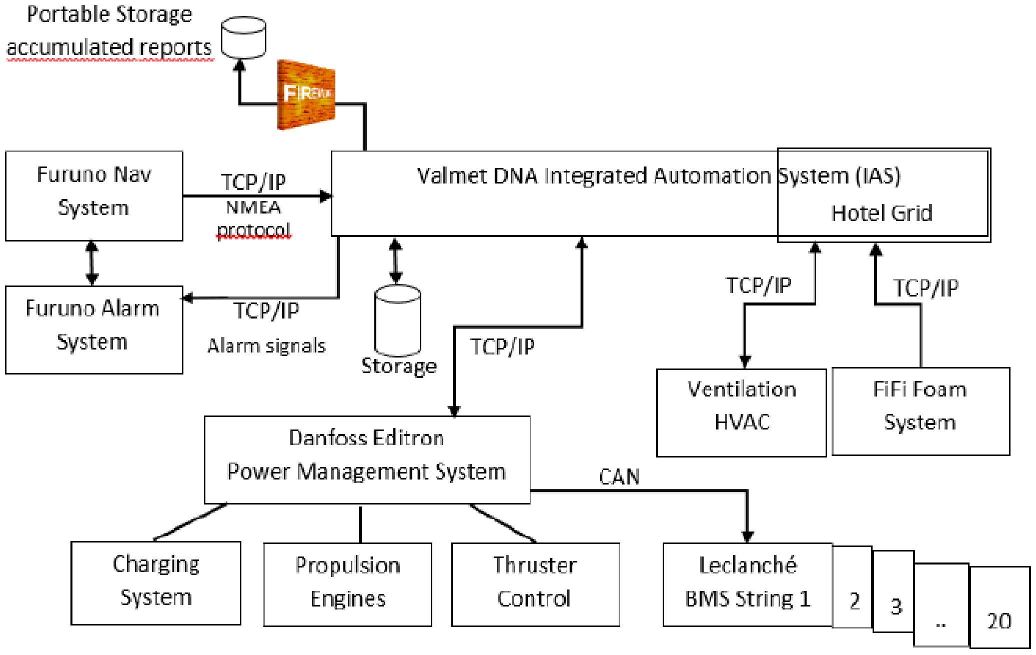


Figure 2 – Schematic of the IAS implemented in the E-FERRY project [1]

ESS integration in the vessel

The worldwide largest battery capacity for maritime use has been integrated as part of the E-FERRY project. A 4 MW peak charge and 4.3 MWh of capacity lithium-ion battery system was integrated in two separate battery rooms. The whole system is aimed to be redundant, each of the rooms consisting of 10 separate strings of batteries, at a nominal capacity of 215 kWh each. The battery pack peak charging power and its shore charging connection will be up to 4 MW, the latter was also developed within the project. Moreover, the whole electrical system has been implemented. The main components are the motor, a reluctance assisted permanent magnet motor technology; the control system, mastered by a DC/AC inverter; and the power electronic systems. These are composed of electric drive train systems that use DC-based distribution for battery charging, which allows each power source to be utilised individually and optimally.

BMS/EMS development

The E-FERRY project battery technology relies on specific NMC-type cells manufactured by project partner Leclanché GmbH. Low weight, fast-charging capability, long calendar and cycle life features have been sought. 2844 cells have been produced for the project, of which 50 cells are intended for certifications and safety testing, and 2794 for the development of the strings of modules and its assembly line. Such cells are monitored at a string level by the Leclanché BMS. The BMS communicates with the global PMS developed by Danfoss via CAN protocol.

Battery fine tuning and balancing has been one of the key tasks of E-FERRY project, due to the dimensions of the implemented system. In this regard, battery balancing, at module level, is done automatically during the night by the BMS and PMS to optimise performance.

As to battery health monitoring, a cyclic counting functionality has been implemented so as to determine the State of Health (SOH) with respect to the initial battery capacity. Energy data extraction and processing is done by the PMS.

Key challenges identified

- Ferry design is not optimised in terms of energy efficiency. Moreover, the reduction in new ferries weight is often not considered.
- Short port stays during the ferry operational schedule require sophisticated electrical charging infrastructure and battery systems for full electric vessels.
- Delivering enough power from the local grid to charge at very high rates during short port stays, as well as transferring such high powers in a safe way in all weather and operational conditions.
- Not all actors of the sector were fully convinced about electric ferries being part of the maritime transport solution.
- Crew competences for fully electrical operation are not yet fully clear.
- Educational requirement for future ferry crews is not in place. In this regard, new job roles/departments will have to be created but some could also be associated with training of existing employees.
- The future of technical solutions, creation of jobs and services within our society may be constrained by the lack of a suitable regulatory environment.

Key learnings identified

- The E-FERRY reported energy savings of up to 50 % and 100 % GHG emission reductions.
- The E-FERRY is 5 % heavier than originally projected, due in particular to design changes to the battery and charging system; this has not affected the average energy consumption (1600 kWh per return trip).
- The E-FERRY prototype is a commercial alternative to traditional Diesel- and Diesel-electric propelled ferries, even if no future emission requirements (penalties) for vessels were considered in the comparative analysis.
- The E-FERRY is a valid commercial alternative from a purely economic aspect. Despite of the higher investments costs, these are paid out after 5-8 years of operation, when compared to best available technology for Diesel-electric propulsion (double battery replacement considered during its lifetime).
- The electrical infrastructure and charging system should be constructed on different owner-terms, which would lead to both lower investment costs and lower costs per-kWh for the charged electricity.
- End-users of the E-FERRY prototype were either “extremely satisfied” or “very satisfied”.
- It is necessary to assign more clear roles and responsibilities in such a complicated project that includes construction of major components.
- Other important savings were achieved via crew cost, as the E-FERRY is approved to sail without a marine engineer. Instead, a service engineer takes care of maintenance.

3.2.2 NAUTILUS

Start date: July 2020

End date: June 2024

Type of project: H2020 research and innovation program under grant agreement Nº 861647

Project coordinator: Deutsches Zentrum für Luft – und Raumfahrt (DE)

Summary: The NAUTILUS project aims at developing, evaluating and validating a highly efficient power generation system fuelled by Liquefied Natural Gas (LNG) for long-haul passenger ships. The to be developed system will cut GHG emissions by 50 % and all other Diesel engine exhaust gas emission components almost entirely. The NAUTILUS project intends to use LNG as a propulsion fuel, with a further reduction of GHG and onboard emission by replacing conventional engines with Solid Oxide Fuel Cell (SOFC)-battery gensets.

Main objectives:

- Develop a complete concept of a fully integrated energy system between 5 and 60 MW for a 1000-passenger expedition cruise vessel and a 5000+ passenger cruise ship.
- Develop, assemble and operate a 60 kW functional demonstrator of the SOFC-battery to validate the design and operation strategies.
- Evaluate the digital design, as well as the physical demonstrator against the marine safety regulations.

Topics related to NEMOSHIP goals:

Technical topics: EMS/BMS, ESS integration in the vessel/vehicle/site, ESS hybridisation.

Project website: https://nautilus-project.eu/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: ESS integration and hybridisation, BMS/EMS development and digital twin (DT)/digital tool development.

ESS hybridisation

NAUTILUS project proposes a hybrid energy system that combines SOFC system of 10x100 kW and a 1x300 kW battery system (BAT) genset. Before hybrid system configuration, an in-depth technology screening of fuel cell and battery systems was carried out (Deliverable D2.1). A less mature SOFC technology was compared to Proton Exchange Membrane Fuel Cell (PEMFC) systems and, ultimately, SOFC has been selected due to higher volumetric power density, higher system electrical efficiency, high fuel flexibility and the possibility of heat and power co-generation that it offers. Hence, being a more suitable option for the cases with less limitation in terms of space and weight. Regarding the proposed hybridisation, due to the lower maturity level of the SOFC technology, few hybrid SOFC-BAT performance and techno-economic data are available. PEMFC-BAT hybridisation is found to be more common since it provides functional advantages like easier system configuration and good dynamic performance. To overcome such issues, a modular genset concept is proposed as shown in Figure 3. The one to be implemented is the micro/mild hybridisation composed of a 1.3 MW hybrid genset and 35 MW internal combustion engine (ICE) which reaches a 50 % electrical efficiency (77 % with heat recovery). A further step on this is the balanced hybridisation where a 50 % hybrid genset and 50 % ICE have been conceptualised. The last step would be the full hybrid genset implementation.

To interface between battery systems and the unitised genset control unit, a specific Battery Management Unit (BMU) will be developed. Such unitised genset control unit requires tailored algorithms for advanced control functionalities.

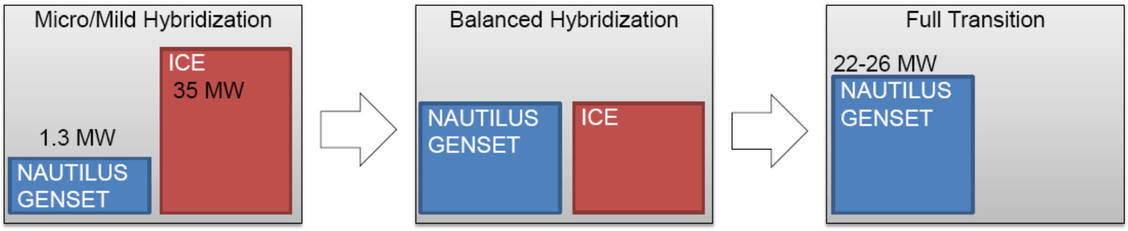


Figure 3 – NAUTILUS modular genset concept [2]

ESS integration in the vessel

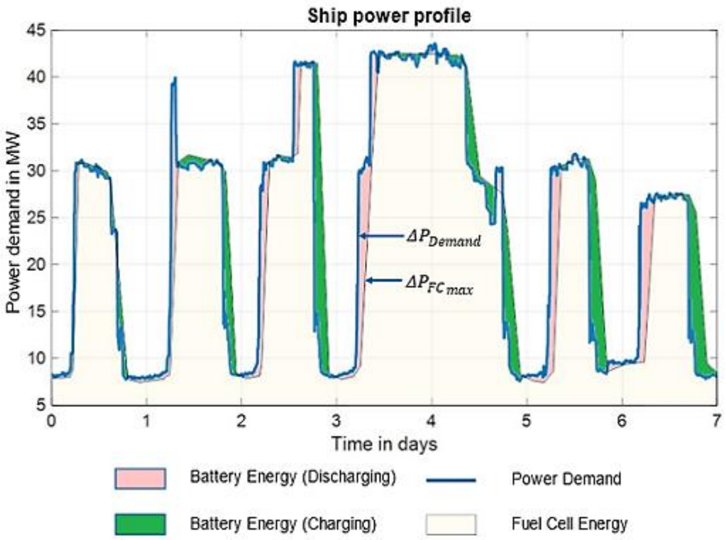
A 60 kW functional demonstrator was integrated in the existing vessel. The proposed hybrid energy system is modular so that the 5 to 60 MW conceptualised system can be easily built in from the functional demonstrator. The targeted power output of 5 to 60 MW will be built of modular genset units of 100 to 250 kW.

The SOFC-BAT system is interfaced with tailored power electronics. In this regard, it has been defined that separate DC/DC converters for SOFC and BAT systems need to be placed in different rooms due to the significant differences in operational conditions (mainly operation temperatures and DC voltage values).

BMS/EMS development

Since both propulsion components are coupled, the power demand will be split between the available sources. The power split was developed to meet two main targets: 1) to guarantee a continuous system operation and 2) to ideally lead to near-optimal fuel consumption and reduce the degradation of the power sources.

The Energy Management Unit (EMU) is the system in charge of the power split. It is designed based on power profile data of multiple cruise ship types provided by project partners. The SOFC is considered to be the primary source of propulsion power, while the battery will be in charge of delivering the load transients. In addition, the EMU is to maintain the state of charge of the battery at an intermediate level (i.e., around 50 % state of charge). An exemplary operation profile of the ship is shown in Figure 4.



The calculated power distribution between the energy sources in the Energy Management Unit

Figure 4 – Hybrid genset power profile and distribution among sources [3]

Digital twin (DT)/Digital tool development

Regarding digital tools in the NAUTILUS project, a Virtual Genset Simulator (VGS) was developed, which can be further integrated into ship energy system simulators. The outcomes from the proof-of-concept (30 kW SOFC connected to battery) will be used in design validation for the virtual twin as well as a foundation for the functional demonstrator (60 kW SOFC coupled with battery).

Key challenges identified

- Viable volumetric power density. Weight and space constraints are key aspects to be optimised in future designs.
- Up-scaling the 60 kW demonstrator to MW size plant.
- Transient capabilities of the hybrid system. The SOFC technology has some limitations in terms of dynamic response, hence the battery system will be in charge of supplying the load fluctuations.
- Cost competitiveness. Tailor-made vessel solutions are costly and the lack of professional skill workers and the capacity to develop such technology make it technically complex.

Key learnings identified

- Volumetric power density and increased overall genset efficiency are key parameters to be optimised in future low emission vessels with limited space.
- Heat recovery and utilization (> 300 ºC) is one of the core advantages of the SOFC-BAT hybridization.
- Specific BMU and control algorithms need to be developed in such innovative systems.
- Modularity is a key feature when trying to scale functional prototypes to multi-MW systems.
- Differences in operation conditions of the hybridised technologies need to be considered for power electronics selection and location.
- Energy management is set to guarantee power supply as well as optimising fuel consumption and asset lifetime.

3.2.3 MARANDA

Start date: March 2015

End date: March 2022

Type of project: H2020 research and innovation program under grant agreement N° 735717 RIA

Project coordinator: Teknologian Tutkimuskeskus VTT Oy (FI)

Summary: In the MARANDA project, an emission-free hydrogen fuelled PEMFC based hybrid powertrain system is developed for marine applications and validated both in test benches and on board the research vessel Aranda, which is one of about 300 research vessels in Europe. Special emphasis is placed on air filtration and development of hydrogen ejector solutions, for both efficiency and durability reasons. In addition, full scale freeze start testing of the system is part of the project scope. When research vessels are performing measurements, the main engines are turned off to minimise noise, vibration and air pollution causing disturbance in the measurements. 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 during measurements, free from vibration, noise and air pollution.

Main objectives:

- Develop an emission-free hydrogen fuelled PEMFC based hybrid powertrain system for marine applications and validate it via durability test benches and operation simulations on board of the research vessel Aranda, which is one of about 300 research vessels in Europe.
- Increase the market potential of hydrogen fuel cells in the marine sector, which have for long lagged behind road transportation. General business cases for different actors in the marine and harbour or fuel cell businesses will be created and therefore the impacts in the whole industry will be notable.

Topics related to NEMOSHIP goals:

Technical topics such as digital tool, ESS integration, ESS hybridisation.

Project website: https://projectsites.vtt.fi/sites/maranda/deliverables.html/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: ESS hybridisation, BMS/EMS and digital tool development, R&D gap definition and dissemination activities.

ESS hybridisation

A hydrogen fuelled PEMFC based hybrid powertrain system is developed for marine applications (Figure 5). Both the fuel cell (FC) system and the H2 storage system are built into 10-foot sea containers. Standard 10-foot containers have the following dimensions:

- Length x Width x Height = 10'/3.05 m x 8'/2.44 m x 8' 6"/2.59 m
- Tare weight = 1 300 kg
- Maximum payload = 10 000 kg

The Aranda ship deck structure is designed to hold the standard container weight and suitable fastening systems are installed on the deck. The FC and H2 system containers have the following characteristics, among others:

- Fire and hydrogen safety mechanisms are integrated into the containers.
- Air inlet and outlet ports for the FC system and container ventilation are made.
- Fire-insulated through-holes for hydrogen and data signal passage between the containers are made.
- Necessary utility power inlet ports are included in both containers.

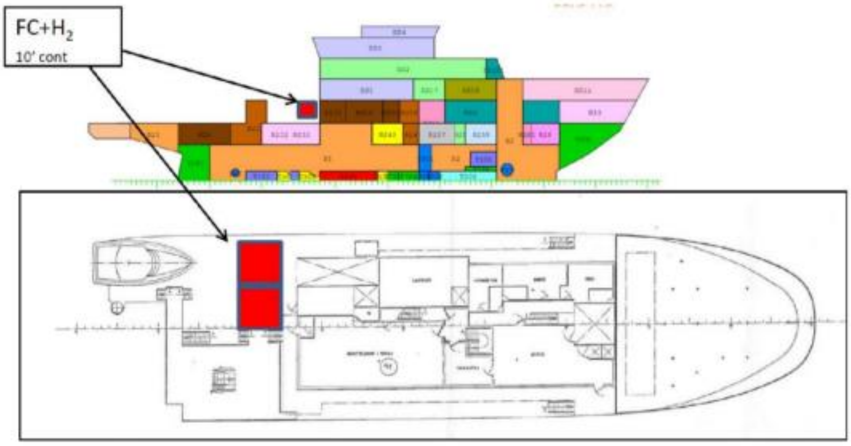


Figure 5 – MARANDA project planned fuel cell and hydrogen installation [4]

ESS integration in the vessel

As part of the project, three sub-systems are installed into two 10-ft freight containers: 1) fuel cell power module (FCPM), 2) power electronics (PE) and 3) higher-level control system (HLCS). A 165 kW (AC) PEMFC system, consisting of two 82.5 kW FCPMs is installed on board the research vessel Aranda.

The FCPM is based on the Swiss Hydrogen model SHA-100-E module (Table 6).

Table 6 – SHA-100-E general specifications (MARANDA) [5]

Nominal power	96,9 kW
Nominal current	300 A
Peak current	450 A
Nominal voltage	323 V
Voltage range	250…500 V
Number of cells	455
Waste heat	82 kW
Dimensions (H x W x D)*	708 x 403 x 528 mm
Weight	98 kg
*Not included: air filter, air mass flow meter, brackets, wiring harness, covers, heat shields, coolant reservoir, compressor inverter	

FCPM includes following components and subsystems:

- Fuel cell stack.
- Cathode subsystem: air compressor, charge air cooler, cathode drain valves.
- Anode subsystem: proportional valves to control flow rates and pressures, purge valve, hydrogen cyclone, heat exchanger for pre-heating fed hydrogen.
- Primary cooling loop: plate heat exchanger, coolant pump, by-pass valves, coolant reservoir, ion exchanger.
- Programmable automotive engine control unit (ECU).

The fuel cell system/container contains the FCPMs, the power electronics as well as the control hardware of the FC & H2 plant. The fuel cells are integrated into fuel cell power modules and two modules are installed in total. Each power module has a dedicated power electronics train up to the DC/AC inverter. In addition to the fuel cell stack, the fuel cell power module includes the fuel cell air feed blower, the hydrogen (secondary) pressure regulator, the hydrogen recycling system.

BMS/EMS development

An analysis of the automation and control system for the pilot ship with fuel cells and energy storage systems is performed as part of the MARANDA project. The control part concerns the fuel cell control. Energy storage system is excluded from the project since there will be energy storages in the main propulsion converter system outside of the scope of the fuel cell powertrain. Energy storages are important, however, for the fuel cells too, since the fuel cell system itself is not maintaining the network voltage nor the network frequency, but only feeding the power to it.

The vessel automation and the power management system are combined into one system in the vessel, which is reducing the number of the external connections. The communication between the vessel systems will be implemented with Modbus/TCP fieldbus. The commands to the main switchboard circuit breaker will be implemented by hardwired signals.

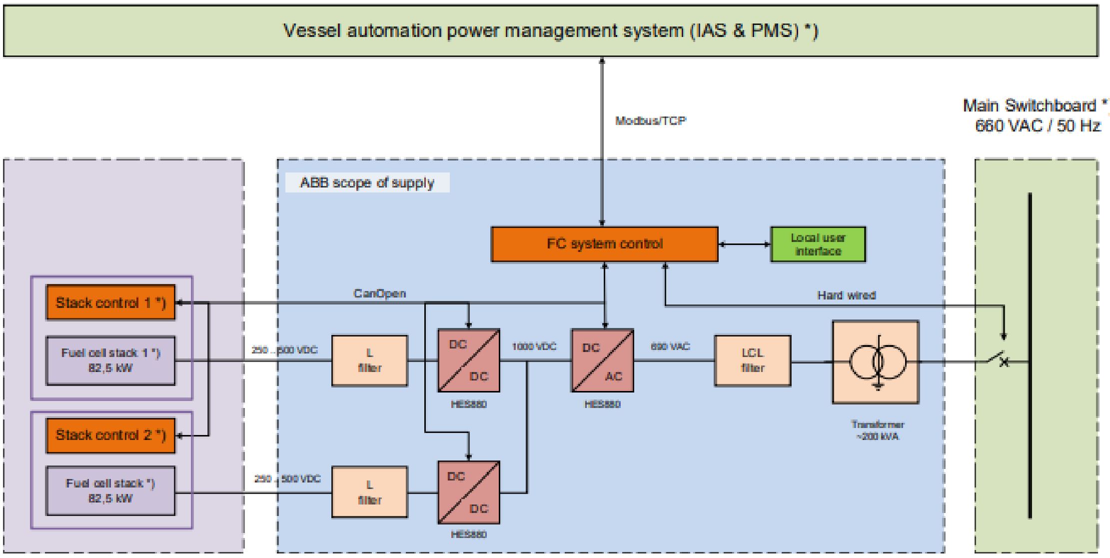


Figure 6 – MARANDA control structure [4]

The basic control principle of the system is power control from the PMS (Figure 6). When the system is running, it will read the power reference value from the PMS and then command the fuel cell system accordingly. The two DC/DC converters will be operating in parallel and dividing the power production equally. The DC/AC converter connects to the DC-link voltage and feeds energy to the main switchboard. It is the power management system that takes care of the power distribution between different power producing units. This will isolate the system level optimisation into the PMS and the fuel cell unit will follow the orders. In case of load transients, the primary source of immediate power should be the emergency storage and the PMS should increase the fuel cell power reference moderately to respect the power increase slopes of the fuel cells. Similarly, the power reference decrease should not be too fast for the fuel cells. Instead, the energy storage can act as a buffer for excess energy.

Digital tool development

The tool is developed following a 3 steps process before the design approach:

1. Definition of marine mobility need:
    - Define and characterise main vessel categories.
    - Identify and quantity main vessel characteristics.
    - Enable users to input their own vessel characteristics and/or overwrite prefilled data coming from a selected category.

2. Identification of FCH solution:

For marine applications, there is no standard solution.

For H2 storage as liquid and gaseous forms, mature technologies were selected. The solution would have to be built based on a combination of fuel cells and storage vessels. The sizing of the FC is based on the power requirement and hybridisation, and for the storage, it is based on the autonomy.

3. Evaluation of adoption of FCH solution (economic and environmental)

The economic assessment includes CAPEX of the new FCH components (and the battery) as well as OPEX essentially made of maintenance and H2 purchase. The full electrification (e.g., the engine) has not been quantified due to challenges in deriving a model which would be able to connect technical parameter needs (such as speed) with sizing of the engines and related costs. Regarding the environmental impact, the project team decided to assess:

- CO_2
- NO_X
- SO_X

Regarding the tool design, the approach includes 5 tabs/steps. The first one is the existing ship (project) description where vessel type is selected or introduced. In the second step, power requirements of the ship under consideration are specified. Then, the energy tab allows to select the energy inputs for the ship. In step 4, description/typical data for FC technologies is presented. And finally, the TCO of the new possible FCH solutions are computed and presented to the user for comparison, as shown in Figure 7.

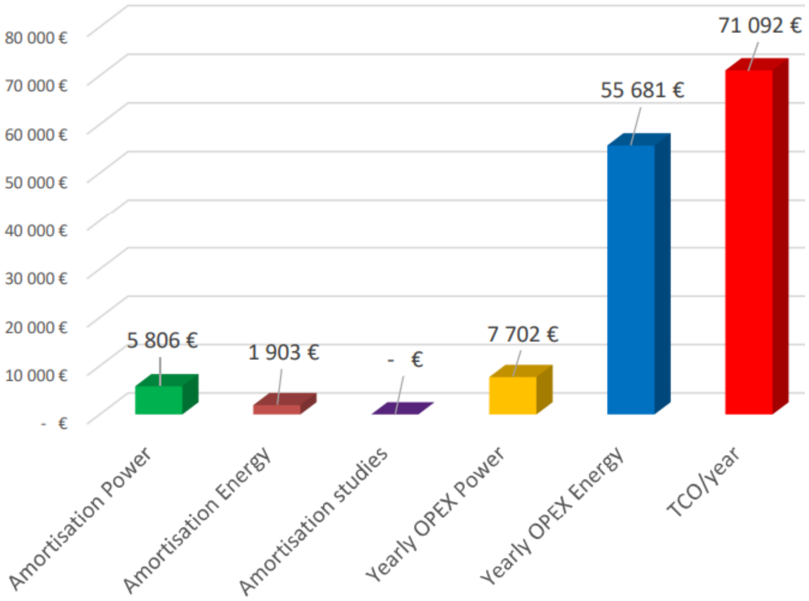


Figure 7 – Contribution of each cost to the TCO (MARANDA) [6]

Moreover, a web-based tool was developed. The web-based tool turns the user experience from designing an FCH solution into testing parameters. The philosophy is then less of offering a precise solution with all required technical, economic and environmental parameters and more a process by which the user can experience the levers for making FCH a solution.

Key interest:

- The fuel cell shows potential to meet the dynamic power demand of the vessel (qualitative observation) when cabling.
- The possibility to automatically compute FCH requirements.

Key challenges:

- Size of the storage system.
- Overall investment needed.
- In lighter boats, refuelling options for this sector are not straightforward enough.
- Cost competitiveness : tailor-made vessel solutions are costly and the lack of professional skilled workers as well as the capacity to develop such technology make it technically complex.

All above mentioned challenges were identified from the start, except the size of the storage system (physical size), which was not foreseen to be a constraint and a feature to be taken into account.

Key learnings identified

A very large number of vessels are overpowered. Therefore, asking vessel owners to describe their current solution is unfavourable to fuel cells, which would benefit from being dimensioned to fit the need. As the power need cannot be reasonably derived from speed and other parameters (unless entering into detailed calculations per vessel category, costly to develop) it was decided to use power need as a primary input.

As speed is a major influencer of engine power rating, it was decided to add in the final tool recommendations to reduce the speed requirement and consequently to reassess power need. The hybridisation itself has proved to be an additional improvement for system optimisation, since it has the ability to cover all necessary requirements. A more straightforward approach to the sizing of the FC was to request from the user an average power need. The fuel cell would be dimensioned to fit this need after end of life (although this is subject to optimisation as well) while taking into account a conservative electric engine efficiency which was confirmed by several stakeholders.

Overall, this approach was viewed as putting too much emphasis on the engineering of the FCH solution which in the end proved too complex to achieve for the vast majority of the vessels. On the other hand, the environmental benefit of the fuel cell was not enough emphasised.

The non-technical objectives are focused on the return on investment for a prospective vessel owner and the identification of drivers.

Dissemination activities

The project was presented at over 20 conferences, workshops or trade fairs. As a part of the project work, a business analysis tool was developed during the first period to support dissemination activities. In the third period, extensive business analysis study for hydrogen fuel cells in maritime applications was prepared. In the last year of the project, the developed fuel cell and hydrogen solution was presented over 20 times at VTT including more than 10 dissemination test runs.

In terms of audiences, the project results were disseminated to the scientific community, industry stakeholders, institutions and regulatory bodies (FCH JU, EDF, CEN CENELEC, US DOE, EU Member States, European Parliament). Additionally, the project aimed at maximising impact through contact with a project advisory board consisting of industry stakeholders and with Regulations, Codes and Standards (RCS) drafting organisations; the advisory board would e.g. provide inputs on business case scenarios.

R&D gap definition

The project maps RCS, existing or under development, affecting the design and the future integration of the powertrain system on board the Aranda vessel. This mapping supports a gap analysis, which aims to ensure a more efficient project implementation. It as well supports an action plan to advance FCH in marine activities. This is in a non-public deliverable (D2.3).

Barriers identification

Some barriers are related to regulatory obstacles and uncertain standards specifically in terms of hydrogen refuelling standards, refuelling station permitting processes, natural gas grid blending limits and safety measure effectiveness for new applications.

3.2.4 JOULES

Start date: June 2013

End date: May 2017

Type of project: FP7-TRANSPORT program under grant agreement Nº 605190

Project coordinator: Flensburger Schiffbau-Gesellschaft mbH & Co KG (DE)

Summary: The EU-funded JOULES (Joint Operation for Ultra-Low Emission Shipping) project aims to reduce carbon dioxide and all other emissions of European-built ships. Given the complex contextual situation of each ship, achieving the objective will require comparison of candidate technologies. The 41-member consortium aimed to develop the predictive tools established by a previous EU project (BESST, Breakthrough in European Ship and Shipbuilding Technologies), enabling such comparison across ships entire lifecycles. The most promising technologies were to be consolidated into three demonstration cases.

Main objectives:

- Focus on the integration of energy saving technologies in the early design stage, using advanced simulation models to be developed for the energy grid of the ship.
- Identify operating profile conditions to provide additional potential for increase of the overall energy efficiency of ships by simulating the energy grid.
- Analyse the whole life cycle of e-fuels and the impact on energy consumption and CO_2-emissions for its production to better understand the possibilities of future adoption.
- Using the results from the Life Cycle Performance Assessment (LCPA) of the eleven application cases, study the most promising technologies in 3 demonstrator cases.

Topics related to NEMOSHIP goals:

Technical topics: DT/tools, ESS integration in the vessel/vehicle/site, ESS hybridisation.

Non-technical topics: training and dissemination activities, R&D gap definition, contribution to new standard/regulations and socio-economic barrier identification.

Project website: https://joules-project.eu/Joules/

The JOULES project has a strong focus on efficiency maximisation of ships, in particular, through electrification and e-fuel adoption and the required design conceptualisation for the technology adoption. Energy recovery technologies for system performance optimisation have also been analysed and an intensive environmental performance analysis was carried out. The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: digital tool development, ESS hybridisation and integration.

Digital tool development

A ship design methodology was developed in the JOULES project. This combines energy grid simulations of the entire ship with an integrated LCPA. The integrated LCPA included (for the first time) a holistic economic and ecological assessment methodology (from well to tank) of fuel production. The developed methodologies have been implemented in the LCPA tool which is utilised to support the decision-making process of the most attractive ship design and technologies by calculating key KPI like net present value, cumulated energy demand, global warming potential, acidification potential, eutrophication potential and aerosol formation potential. The methodology is aligned with ISO 14040.

ESS integration in the vessel

The integration and use of different energy storage technologieswas considered, in particular batteries paired with renewable energy sources like solar PV. The main goal of its implementation is to prevent energy waste and reduce emissions within the vessel, matching power demand and production at every moment. Smart power management strategies were used to reach the mentioned goals.

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.

ESS hybridisation

The hybridisation of the ship energy system with existing technologies of primary and secondary energy conversion was analysed in the project. This has been seen as an intermediate step to the zero emission or fully electrified solutions.

Key challenges identified

- Identify the optimum combination of choice of sustainable fuel and on-board ship technologies to address the challenge of cost effective GHG reductions.
- Find specific equipment suppliers, mainly when it comes to innovative technologies.
- Projecting a ship is a very complex process involving information from many stakeholders in the early design stage.
- Due to the huge amount of individual components, a detailed Life Cycle Assessment (LCA) is far too much work and impossible to carry out in the early design stage.
- The calculation of some environmental KPI was disregarded due to the high complexity.
- Finding the balance between waste heat recovery system dimensions and cargo capacity is complex; the same applies to the system design.

Key learnings identified

- Ship operators must rely on software for decision making due to the complexity and urgency of the problem. Moreover, they will take into account most of the above-mentioned factors and instantly propose a loading scenario which reconciles several operational, economic and maritime criteria while permitting the reduction of fuel consumption.
- For substantial GHG emissions reduction, energy grid simulation was identified as a key short-term measure which could also help for contract negotiation (initial) phases.
- Energy grid optimisation could improve the environmental performance by up to 20 %.
- Fuel production environmental impact should always be considered in the decision-making process. This is mainly to the fact that, by using sustainable fuels from renewable energies, environmental impacts potentially are shifting from operation phase to energy production phase.
- As previous steps to full electrification or e-fuel adoption, primary energy converter efficiency augmentation and energy recovery system implementation have been seen as strong alternatives.
- Developing and building these innovative ships will cost a lot of time and money and there will still be risks that technologies might not be in place as required.

3.2.5 LASTING

Start date: January 2021

End date: December 2023

Type of project: A Coordination and Support Action (CSA) funded by the H2020 research and innovation program under grant agreement Nº 101006923

Project coordinator: Shipyards and Maritime Equipment Association of Europe (BE)

Summary: The EU-funded LASTING project aims at increasing the engagement of the broader waterborne transport sector in European research, development and innovation activities. The project will focus on the development of a communication strategy that encompasses a plug-and-play system for participation in European, national or regional strategic maritime and/or inland waterway transport events. The project also aims to implement a communication campaign that will last beyond the project completion.

Main objectives:

- Increase the engagement of the broader waterborne transport sector in European RD&I activities, by developing a communication strategy, and implementing a long-lasting communication campaign beyond the lifetime of the project.
- Develop a plug-and-play system for participation in European, national or regional strategic maritime and/or inland waterway transport events.
- Ensure a durable implementation of the concepts and materials developed in the framework of the project.

Topics related to NEMOSHIP goals:

Non-technical topics such as training and dissemination activities, R&D gap definition and socio-economic barrier identification.

Project website: https://cordis.europa.eu/project/id/101006923

The LASTING project does not focus on technical aspects but on finding methods to increase the engagement of the waterborne transport sector in RD&I activities. Several non-technical innovations of LASTING are valuable/useful for NEMOSHIP. The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: dissemination activities and R&D gap definition.

Dissemination activities

The LASTING project has identified several needs for the waterborne transport sector regarding RD&I project information dissemination. Some of the key insights so far selected for the present analysis are the following:

- Information does not reach the right people thereby new communication campaigns might be needed.
- There is information available on technical aspects, but not much on the economics and business models related to technical innovations. Moreover, there is not much information on the uptake

of such innovations that come from EU RD&I projects. Organisations have a great need for information in the uptake phase, in which innovations are applied in a real business environment.
- EU RD&I projects websites should be better structured and provide more information. Besides, it would be interesting that these websites remained online for a longer period after the project end.
- Although information is widely available, it is not in a coordinated way, being difficult for an organisation to filter out the relevant information. Therefore, more intuitive RD&I project information filtering would be very helpful.
- Companies, particularly SMEs, may not be fully aware how business models are going to change due to climate and circular economy targets.

R&D gap definition

An extensive gap analysis on participation in research activities has been carried out during the project, with a clear focus on how to exploit the obtained knowledge and how to connect different stakeholders within the waterborne transport sector. In this regard, a handbook on tools and recommendations to address innovation needs has been developed. The following points can be highlighted out of it:

- It is necessary to work on easy to read and understand information sources, especially for SMEs which may be less informed about project opportunities and EU RD&I project results. Organisations like industry associations and other non-profit organisations should play a stronger role in this regard.
- Much of the critical information from RD&I projects is not made public, which makes it impossible to follow up on the detailed results.
- It is fundamental to try to shorten the relatively long time needed to go from an idea to an EU project, since the waterborne transport market is moving really fast.
- A better link to information from relevant RD&I that may come from other sectors could be beneficial due to the multidisciplinary of the sector itself.
- There is a partial mismatch in RD&I activities and implementation between public bodies and private companies.

Key learnings identified

- More information on technology/innovation from EU RD&I projects is needed. Currently, it is sometimes difficult to identify which are the relevant business opportunities.
- Reported information from EU RD&I should be better structured on the website, as well as better filtered so as to ease users value extraction. Information accessibility has also been identified as a bottleneck in this regard.
- Some of the abovementioned gaps could be covered by industry associations and other non-profit organisations.

3.2.6 COLUMBUS

Start date: March 2015

End date: February 2018

Type of project: H2020 research and innovation program under grant agreement N° 652690

Project coordinator: Bord Iascaigh Mhara (IE)

Summary: The COLUMBUS project intends to capitalise on the significant investment of the European Commission in marine and maritime research by ensuring accessibility and uptake of research Knowledge Outputs by end-users such as policymakers, industry, science stakeholders and the wider society. COLUMBUS aimed to ensure measurable value creation from research investments contributing to sustainable blue growth within the timeframe of the project.

Main objectives:

- Adopt proven methodologies and, building on significant past work, identify end-user needs and priorities. Additionally, identify and collect "Knowledge Outputs" from past and current EC projects. Transfer will be achieved and measured through tailor-made knowledge transfer methodologies.
- Carry out strategic actions to enhance the visibility and impact of research to stakeholders and European citizens.
- Working with funding agencies and stakeholders, examine the feasibility of improved systems and processes to ensure measurable value creation from research.

Topics related to NEMOSHIP goals:

Non-technical topics such as training and dissemination activities, R&D gap definition, stakeholder interaction and socio-economic barrier identification.

Project website: https://www.columbusproject.eu/

The COLUMBUS project does not focus on technical aspects but on innovating in knowledge transfer to foster blue growth. Several non-technical innovations of COLUMBUS are useful/valuable for NEMOSHIP. The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: dissemination and training activities, R&D gap definition and socio-economic barrier identification.

Dissemination activities

In the COLUMBUS project, specific knowledge acquisition and transfer methodologies (Figure 8) were developed with the ultimate goal of promoting growth for the blue economy. These methodologies are condensed in the so-called "Knowledge Transfer Cycle" performed by an established "Knowledge Fellowship"; a network of nine full-time (minimum 24 person months each), "Knowledge Transfer Fellows", one for each "Competence Node". Each of the competence nodes has a leader, the "Node Lead", in charge of gathering the information and interacting with its knowledge fellows and the corresponding WP leaders. Knowledge fellows are the ones in charge of acquiring information from other experienced partners and sharing it with their corresponding node lead.

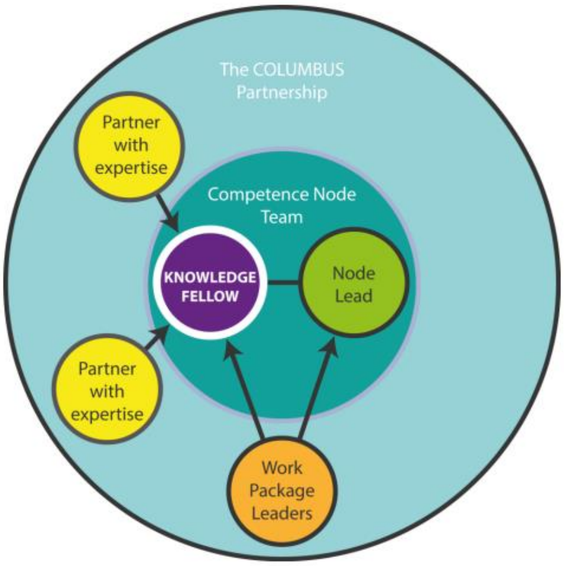


Figure 8 – Structure proposed for knowledge transfer in the COLUMBUS project [7]

Several steps were implemented to ensure that the transfer is strategic, coordinated, and effective (Figure 9). These steps are progressive and are based on a set of templates that need to be completed for a better harmonisation of the information and the process itself.

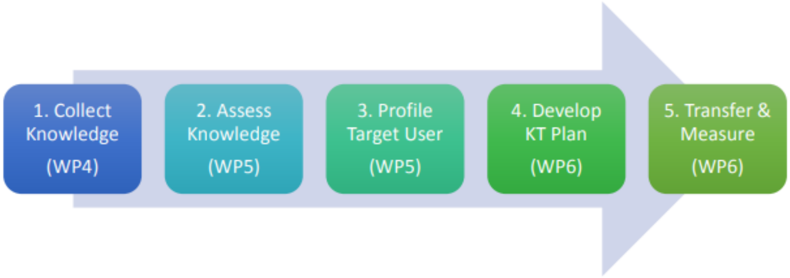


Figure 9 – Steps implemented in the knowledge transfer methodology [7]

Training activities

Internal capacity training activities were carried out during the project. Corresponding knowledge fellows are the ones in charge of offering those training activities to the rest of the COLUMBUS partnership. There are specific learning objectives to be satisfied, all of them related to the knowledge transfer methodology developed. A 48-page training handbook containing the methodology and its associated templates was developed for the internal training courses. Four internal training courses were run over the course of the project.

Also, free external training courses were held once the methodology had been validated by the project partners. Training targeted two main groups: funding agencies and researchers.

Following every training activity, feedback from participants was sought and observations were made to learn from every event and improve the content and approach for the next training activity. The most frequent and highly emphasised response was to have more expert support, more training and further capacity building, particularly in:

- Developing impact plans for project outputs.

- Funding opportunities for Knowledge Transfer initiatives.
- Stakeholder identification and engagement.

R&D gap definition

During the project execution several gaps related to R&D activities were identified. Many of them are indirectly related to the R&D activity considered but impact heavily on it. For instance, aspects like communication gaps and skilled workforce availability. In particular, these are the most repeated gaps:

- Transdisciplinary and participation of key stakeholders of all marine and maritime sectors is a key aspect needed to foster innovation in the sector.
- Science-policy communication needs to be improved, particularly when it comes to coordination of different sectors and actors in the maritime sectors.
- It is necessary to foster the cooperation and communication with policy and scientific actors using platforms like WATERBORNE or EU collaboration projects.
- Scarce awareness for environmental societal challenges in the marine environment which require technological solutions.
- Significant industrial barriers need to be overcome to develop technological innovations. For instance, the limited development of cross-sectoral tools or the reduced efforts on greening our ocean economies.

Socio-economic barrier identification

Some general or cross-sector barriers were identified in a first stage. The most noticeable were: under-investment in knowledge, poor access to finance, the high cost of intellectual property rights, slow progress towards interoperable standards, ineffective use of public procurement and duplications in research.

Particularly, some other socio-economic barriers for blue economy growth were identified:

- The lack of skilled workforce shows a clear existing skill gap.
- The uncomplete establishing/adoption of the appropriate legal framework.
- The lack of free and open-access multi-purpose data repositories and portals.
- The need for innovative and environmentally friendly technological solutions.

Key learnings identified

- The initiative created an extended transnational partnership representing all aspects of the research value chain, including funding bodies, researchers, communication experts and knowledge users. Project partners developed a step-wise, “COLUMBUS Knowledge Transfer Methodology“ based on the identification and collection of knowledge outputs.
- The initiative focused on ensuring value creation from research. The project aimed to go beyond simply making knowledge accessible. It focused on mining funded projects for knowledge that had the potential to fill knowledge gaps and overcome bottlenecks and transferring this knowledge directly to target users to support the implementation of various marine strategies and policies.
- The combined efforts of the project team led to the review of just under 1 000 projects, the collection of almost 1800 knowledge outputs and over 60 cases of successful knowledge transfer.
- COLUMBUS examined the feasibility of implementing knowledge transfer approaches into European and national funding systems. This resulted in a set of recommendations to funding agencies being delivered to the European Commission.

- The end user groups strongly agreed (66%) that there is not enough engagement with stakeholders/end users, rating this to be the top barrier for efficient knowledge transfer. Additional barriers identified include the lack of resources and/or expertise in knowledge transfer within their organisation and/or region (51%) and getting the scientific/engineering community engaged in knowledge transfer opportunities (49%).

3.3 Road mobility projects

3.3.1 ORCA

Start date: 01 October 2016

End date: 30 September 2021

Type of project: H2020 research and innovation program under grant agreement N° 724087

Project coordinator: TNO - Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (NL)

Summary: The ORCA project aimed to design an affordable and clean hybrid bus and freight truck. More specifically, ORCA hads the ambitious goal to develop an IVECO multimodal hybrid bus and VOLVO distribution hybrid truck with an extended full electric range from 10km to 30km. Vehicles will be equipped with innovative PHEV rechargeable energy storage (RES) systems, designed specifically for each vehicle application. The total cost of ownership (TCO) remains the same in comparison to their conventional counterparts. Bringing the cost of a hybridised vehicle down requires generating a combined impact on overall system cost, efficiency, and operational cost. Moreover, the newly developed applications will have the same performance and functionality. ORCA had set itself specific targets: Improve the hybrid powertrain efficiency up to 5% compared to actual IVECO hybrid bus and conventional trucks through optimised RES selection & sizing and by improving the energy and combustion engine management.

Main objectives:

- Reduce the TCO to the same Diesel vehicle TCO level, targeting over 10% system cost premium reduction compared to actual IVECO hybrid bus and VOLVO conventional truck with the same performances, same functionalities and operative cost; moreover, targeting up to 10% RES lifetime/energy throughput improvement.
- Improve the hybrid powertrain efficiency up to 5% compared to actual IVECO hybrid bus and conventional truck through optimised RES selection & sizing and by improving the energy and ICE management.
- Improve the electric range from 10 km to 30 km by adding the PHEV capabilities and optimising the RES capacity.

Topics related to NEMOSHIP goals:

Technical topics: energy management strategy, ESS hybridisation, RES, codesign optimisation.

Project website: https://h2020-orca.eu/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: development of a modular and scalable rechargeable storage system and co-design optimisation method.

Development of a modular and scalable rechargeable storage system

A modular and scalable RES (i.e., hybrid concepts including high-energy battery and high-power Li-capacitor) has been developed for the heavy-duty vehicle. The lifetime model of battery will be performed. VUB has performed an extended lifecycle tests to investigate the impact of the proposed RES technology for the different demonstrators based on the stress factors (current rates, depth of discharge and operating temperatures). The output of this work was used to develop a state of health algorithm. A lifetime test methodology was developed at the MOBI's Battery Innovation Centre in VUB for analysing the performance of NMC 40 Ah battery technology and for evaluating the variation of different battery ageing parameters (Figure 10 and Figure 11).

Figure 10 – Open-top picture of the battery during factory test at Bluways (ORCA) [8]

Figure 11 – Top picture of the LiC during power split testing at VUB (ORCA) [8]

Co-design optimisation method

The co-design is optimal with respect to TCO (Figure 12). One challenge is to estimate costs of HW components, fuel, and electricity. Such prices are often confidential, and it is also difficult to predict the future prices of these costs. One way to handle this difficulty is to consider a range of prices for of

HW components, fuel, and electricity. This approach solves the confidentiality problem but, on the other hand, it increases the level of complexity. The co-design sums up to be a highly complex problem and there is a need to approach the complexity in a structured and methodical way.

The focus of the activities was on:

- Development of a methodology to handle the complexity problem.
- Development of a low-fidelity modelling that will be used for evaluation and for control design.
- Development of an optimal predictive controller that can be used in the TCO evaluation.

The co-design results were satisfying in the sense that it gives us a toolbox for evaluating electrified drive trains on various transport missions.

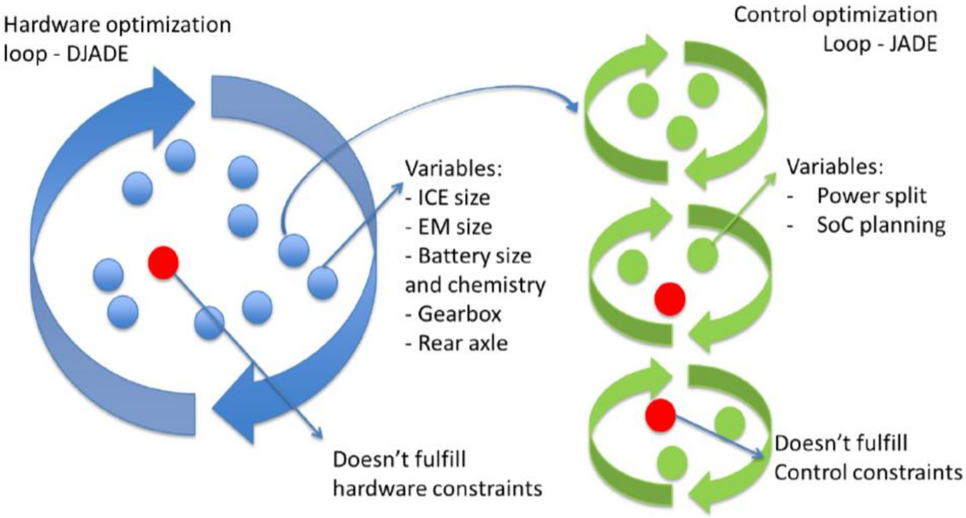


Figure 12 – Co-design and sizing (ORCA) [9]

Key learnings identified

- Virtual simulation framework is developed into an optimisation framework, enabling the user to size the capacity of the energy storage system and select the optimal cooling system among diverse options. In this framework, a multi-objective particle swarm optimisation algorithm was developed and implemented.
- The power sharing between high-power and high-energy storage systems is optimised to control and shift the high-frequency and high-slope currents from the lithium-ion battery pack to lithium-ion capacitor in terms of life-time improvement.

3.4 Stationary projects

3.4.1 HYBRIS

Start date: January 2021

End date: December 2023

Type of project: H2020 research and innovation program under grant agreement N° 963652

Project coordinator: IDP Ingenieria y Arquitectura Iberia Sl (ES)

Summary: The goal of the EU-funded HYBRIS project is to optimise hybrid electrical energy storage systems for use in microgrid applications. Project activities will be related to the design and characterisation of novel hybrid energy storage systems and power electronics, and their integration into the grid. The consortium combines expertise in advanced materials and energy storage technology development, covering the whole chain from cell development to system integration. The systems will be validated in three use cases: energy services in island grids, energy services in private grids and electric vehicle charging stations.

Main objectives:

- Optimisation of advanced hybrid systems as high-performant, cost-effective and environmentally friendly solutions in microgrid applications.
- Viable and cost-effective use and integration of novel HEES system coupled with innovative microgrid system, local RREE generation and loads (in particular residential, tertiary buildings and EV charges stations).
- Integration and validation of a suite of technologies, tools and methods enabling their easy application and massive deployment.
- Technical optimisation of the HEES system in 3 use case applications covering respectively 1) Energy services in island grids 2) Energy services in private grids 3) EV charging stations in e-mobility.
- Optimisation and integration of the storage system.
- System validation by using the 3 demonstration sites.
- Leverage knowledge, key exploitable results, adapted business models and market-oriented dissemination for maximizing impact and wide adoption of these novel heating and cooling technologies and approach.

Topics related to NEMOSHIP goals:

Technical topics: DT/tools, ESS integration in the vessel/vehicle/site, ESS hybridisation, and services in the cloud.

Non-technical topics: training and dissemination activities, LCA & environmental issue analysis, and socio-economic barrier identification.

Project website: https://hybris-project.eu/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: digital twins tools, ESS hybridisation and integration, advanced battery management system in the cloud, LCA & environmental issue analysis, training and dissemination activities.

Digital Twins tools

The Typhoon HIL Control Center (THCC) seeks to model the power stage of power electronic devices to test control software using the hardware-in-the-loop (HIL) methodology, in which the power stage is a high-fidelity emulation connected to the control software. Using Digital Twin for HESS (DTH) technology, the software layer of grid-tied devices can also be modelled using signal processing components and third-party DLLs or ANSI C software code. The combination of high-fidelity real-time modelling of the power stage and identical behavioural control constitutes a digital twin of the HESS. In the ESS domain, digital twins are understood to be high-fidelity real-time virtual representations of smart power electronic devices (DC-AC, DC-DC, and AC-DC converters/inverters for each type of energy storage in a HESS) and the other relevant parts of the HESS (protection layer, subway cables, etc.). These digital twins also accurately represent the thermal behaviour of individual power-electronics devices in the system.

The DTH can be used to set up a digital shadow (DS), which is a virtual representation of the power units and systems of a physical HESS installation that is fed by real data from the site. It can be used for preventive maintenance, verification, and validation of software updates to HESS control systems, assessment of financial benefits of implementing new control algorithms that optimise the operation of HESS to the requirements of its owner, operators, and the grid, thus improving the energy efficiency, performance, and lifecycle management. In short, the digital twin approach makes it possible to support the entire HESS system lifecycle.

ESS integration in microgrids

The developed HESS is coupled with the development of a breakthrough Battery Management System, Novel Power Electronics and an advanced Power Management System which is fully integrated with Energy Management Systems (EMS) and grid systems.

This high-performing, cost-effective and environmentally friendly solution is for microgrid applications. Its power and energy applications are validated in both grid and behind-the-meter market segments through its three pilot sites, which will attend to each specific power and energy needs, response time and discharge time, covering applications from second to several hours.

- Messina, Italy: Local residential energy community integrated in island grid.
- Vorhout, Netherlands: Deployment of energy services within local energy community. Virtual demonstration of customer-owned system with stacked arbitrage and FCR for residential building with net metering tariff.
- Brasschaat, Belgium: Development of new flexibility services under EssA model or C&I business park with high solar penetration.

ESS hybridisation

The project integrates a combination of high power and fast response performant Li-ion battery based on LTO and Aqueous Organic Redox Flow batteries (AORFB). The high energy efficiency and fast response of the LTO, whose storage capacity is expanded thanks to the AORFB, results in a final system capable of covering a large part of the needs that an energy storage system may have, saving investment and gaining performance. It is thus possible to reduce the total size of the battery system (reducing the investment cost) without losing the performance required for an application of this type. At the same time, the life expectancy is prolonged for both types of batteries. CAPEX and stored kilowatt-hour cost are reduced, and operative range is extended in terms of services offered, storage time, peak energy and power releasable, working temperature accepted.

Advanced battery management system in the cloud

The Advanced Battery Management System (ABMS) and its related power electronics will be a software solution that will be interfaced with the EMS in order to obtain all the HESS operation data and to provide relevant information on HESS state through both alarms/early warnings and continuously updated HESS battery models as in Figure 13.

The EMS will act as central controller and orchestrator by communicating with the other control levels making in the cloud the global optimisation of the whole hybrid system. It receives the data from the ESS technology status (i.e. SoH, SoC, Temperature, etc), the local measurements from the point of common coupling as well as weather forecasting and market bids, aiming to optimise the usage of each technology to extend its life-time.

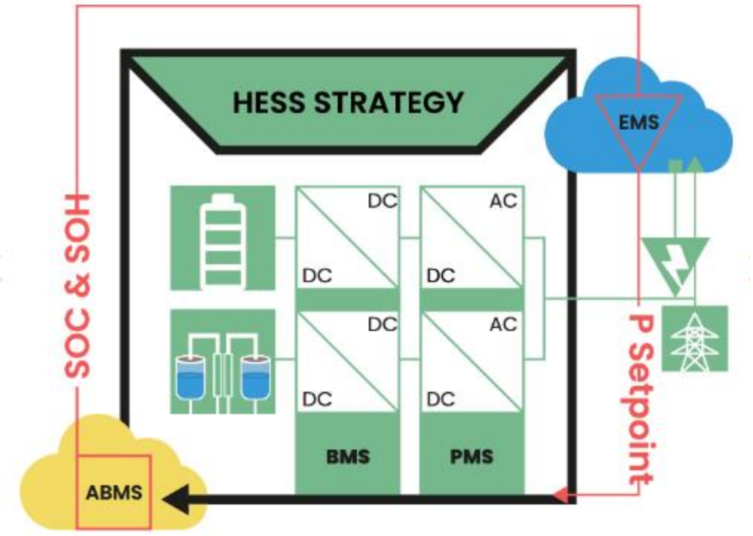


Figure 13 – HYBRIS advanced BMS and power electronics [10]

Implemented in a server in the cloud, the Advanced BMS solution will benefit from more computational resources with the possibility to develop further complex storage system models. In addition, these diagnostic tools will advantageously help the HESS to detect potential BMS failures or errors. Moreover, in case of large HESS, the ABMS will be able to aggregate monitoring data from different BMS and thus achieve better battery state estimations.

LCA & environmental issue analysis

LCA evaluates the environmental burden of either goods or services. It considers the whole product lifecycle: from resource extraction, through production, use and recycling, up to disposal of remaining waste. The standardised framework and guidelines for LCA are given by ISO 14040/14044 standards (ISO, 2006a, 2006b). It is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

In the HYBRIS project, the objectives and scope phase aim to gain an early insight into the sustainable performance and improvement opportunities of the two battery technologies. For the battery manufacturing results, two different questionnaires were prepared, one for each battery technology. The purpose of these questionnaires was to ask the manufacturing companies involved in the project to disclose the required information on material and energy inputs and outputs of the production processes.

After identifying the materials of the different elements inside the battery, LCA was carried out by technology and evaluation of the impact in the following aspects.

- Global warming GW (kg CO_2 eq)
- Stratospheric ozone depletion SOD (kg CFC11 eq)
- Terrestrial acidification TA (kg SO_2 eq)
- Human carcinogenic toxicity HCT (kg 1,4-DCB)
- Human non-carcinogenic toxicity HNCT (kg 1,4-DCB)
- Land use LU (m2a crop eq)
- Mineral resource scarcity MRS (kg Cu eq)
- Fossil resource scarcity FRS (kg oil eq)
- Water consumption WC (m^3)

Finally, the results of the inventory analysis and impact assessment phases were interpreted in relation to the objectives of the study.

Training activities

Some internal and external training activities were carried out to encourage the exchange of knowledge within the consortium and potential stakeholders, professionals, researchers, students and the general public.

In case of external training, knowledge generated within the project will be included in academic and professionals courses promoted by the partners. Training will also be provided to demo users of HYBRIS becoming first adopters and champions.

Regarding internal activities, innovation management and exploitation trainings for the project partners will be organised to optimise the potential use of the generated results during the project, focusing on IPR, commercialisation of research result, licensing-in and licensing-out, technology transfer, business planning, marketing management, financing of innovation, financial and cash-flow management). For example, project partner COMET imparted a workshop on exploitation during the 2nd general assembly. The objective of this workshop was to review the concepts linked to exploitation as it is an on-going activity throughout the project.

Dissemination activities

Apart from the project public deliverables, the project team has prepared different communication materials such as project brochure, presentation, booklet, poster, and roll-up. They may have used them in different events. For example, they made a workshop titled “Energy storage and its crucial role in the energy transition with focus on hybrid solutions” (23^{rd} June 2022). They also published a newsletter related to project development.

All these materials are accessible on their webpage which has also been created for the promotion/dissemination of the project. Additionally, they also have Twitter, YouTube and LinkedIn accounts to share project information and progress.

Key learnings identified

- At the beginning of the project, it is important to identify constraints related to operating conditions, installation requirements and safety issues.
- Process communication interfaces will define the operation of the system, so they must be properly selected.
- The system should be effective and offer service flexibility from the user point of view.
- The lack of input data can affect the results obtained, such as lack of consumption behaviour and generation capacity data to estimate energy cost. Any assumption, model and approximation will influence into the final assessment. LCA can help to reduce some of those uncertainties.
- To improve the lifecycle of batteries and their environmental performance, more efficient manufacturing processes are suggested, for example to reduce electricity and water consumption. Alternatively, cleaner energy resources could be used, as the rate of renewables in the electricity consumed increases. Together with the integration of recycled or biomaterials in the HESS.
- The HESS is containerised to make easier the transportation, considering the prototype dimensions.
- For the testing of the real prototype, it must be considered as an integrated system, including BESS (Battery Energy Management System) and PCS (Power Conversion System). It will include HESS model, virtual demonstration site test, grid emulation model and historical data. This way the integration of the model into the electric system will be possible.
- In order to address standardisation, it could be interesting to join international technical committees (TCs) to be updated. Dissemination material could be delivered to TCs and even develop new standard(s)s or reference(s).
- Communication materials are important to keep all project stakeholders and interested parties informed. They should be updated as the project develops. In this way, fundamental knowledge and deeper understanding is ensured, which encourages greater engagement and active participation.
- In case of activities open to the general public, prior dissemination is recommended to maximise the relevance and attendance, extending the reach through the webpage or social media. These activities can also help to collect data from the attendees and realise a market analysis.

3.4.2 iSTORMY

Start date: 01 December 2020

End date: 31 May 2024

Type of project: H2020 research and innovation program under grant agreement N° 963527

Project coordinator: Vrije Universiteit Brussel (BE)

Summary: The iSTORMY project is an EU-funded research and innovation project which will propose an innovative and interoperable hybrid stationary energy storage system based on: modular battery pack (stacks/modules), modular PE interface, universal self-healing energy management strategy (SH-EMS).

Main objectives:

- Develop an interoperable and modular Hybrid Energy Storage System (HESS)
- Demonstrate various use cases and seamlessly interface the grid to provide multiple services at minimum cost, such as a combination of load levelling, frequency regulation, provision of backup power.

The main project objectives are summarised in Figure 14.

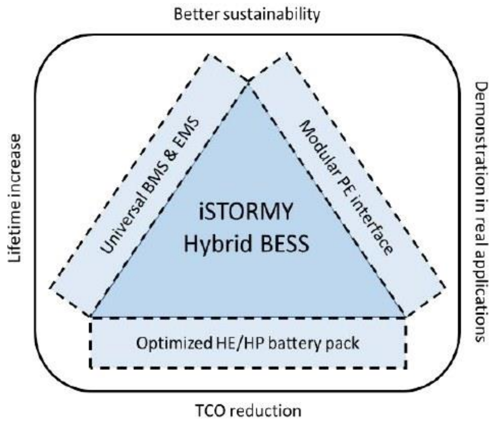


Figure 14 – Positioning of iSTORMY objectives [11]

Topics related to NEMOSHIP goals:

Technical topics: digital twin, codesign optimisation.

Project website: https://istormy.eu/

The HESS consists of 1st and 2nd life batteries, modular power electronics and thermal management and an intelligent control structure. Managing this is a complex and challenging task since it involved combining components of different natures (e.g., electrical, mechanical, thermal or chemical) and of different dynamics into a single system.

iSTORMY looks at the entire system integrating innovations at the power electronics, battery stack and energy management system level including the possibility to use 2nd life EV batteries, as shown in Figure 15.

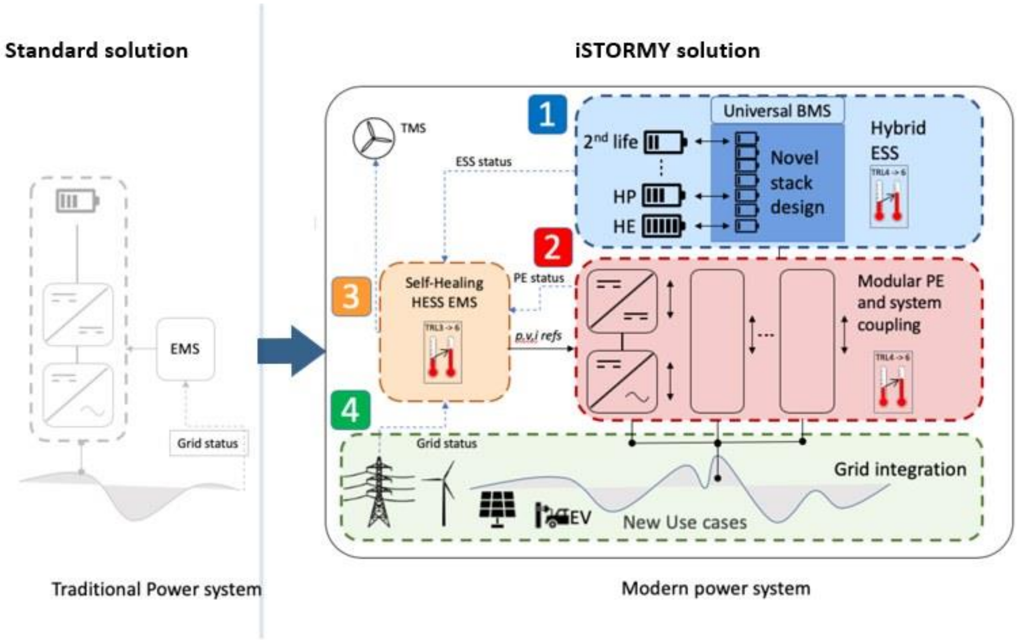


Figure 15 – Graphical representation of iSTORMY solution [11]

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: digital twin modelling framework and co-design optimisation method for power electronics interfaces.

Digital twin modelling framework

The DT modelling aims to capture the dynamics of the physical PE system towards loss estimation and junction temperature estimation so that operational degradation can be assessed, and real-time operation can be closely monitored in the self-healing Energy Management Strategy (EMS), during physical asset operation. The DT framework comprises three parts (Figure 16): (1) component stage modelling, (2) power stage or system level modelling and (3) data-driven DT modelling. As shown in the Figure below, the modelling outcome of the first stage is used for the system-level modelling to capture the dynamics in parallel with the physical PE interface. The data from these dynamics of the PE interfaces is fed into a data-driven modelling routine to replicate as closely as possible the physical PE interfaces behavior and generate a DT.

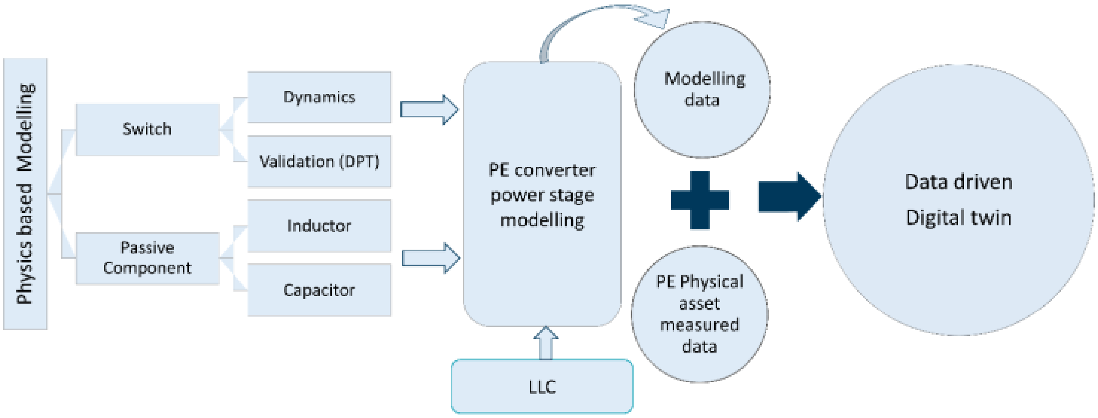


Figure 16 – Conceptual building block for DT modelling (iSTORMY) [12]

Co-design optimisation method for power electronics interfaces

A fast co-design optimisation and sizing framework for the modular hybrid HESS is developed based on the system simulation to find the optimal sizing of HESS components in terms of longer lifetime, higher efficiency, and lower cost (Figure 17). The system simulation is based on low to medium fidelity models of the battery modules and the power electronics (PE) interfaces. Also, a first iteration of the EMS is developed to ensure the co-design of the system. Different cell technologies and PE interfaces are considered in terms of high power and high energy battery pack to build the HESS and meet the load profile requirements. Based on a multi-objective genetic algorithm optimisation, the optimal solutions are obtained and compared in terms of system cost over 10 years lifetime, system efficiency, battery lifetime, and PE interface lifetime. Finally, the iSTORMY solution is selected with the description of the battery packs (chemistry, capacity, first- or second-life batteries) and PE interface architecture, topology, and size.

Key learnings:

- LFP cells are selected for the HE battery pack, and NMC cells are considered for the HP battery pack, based on the consortium estimations and information available with regard to cost and cyclability. In particular, 2nd-life batteries are not a viable option at the time of reporting (Nov 2021) due to relatively high cost and limited market maturity, but they may become a very interesting option in the coming years.

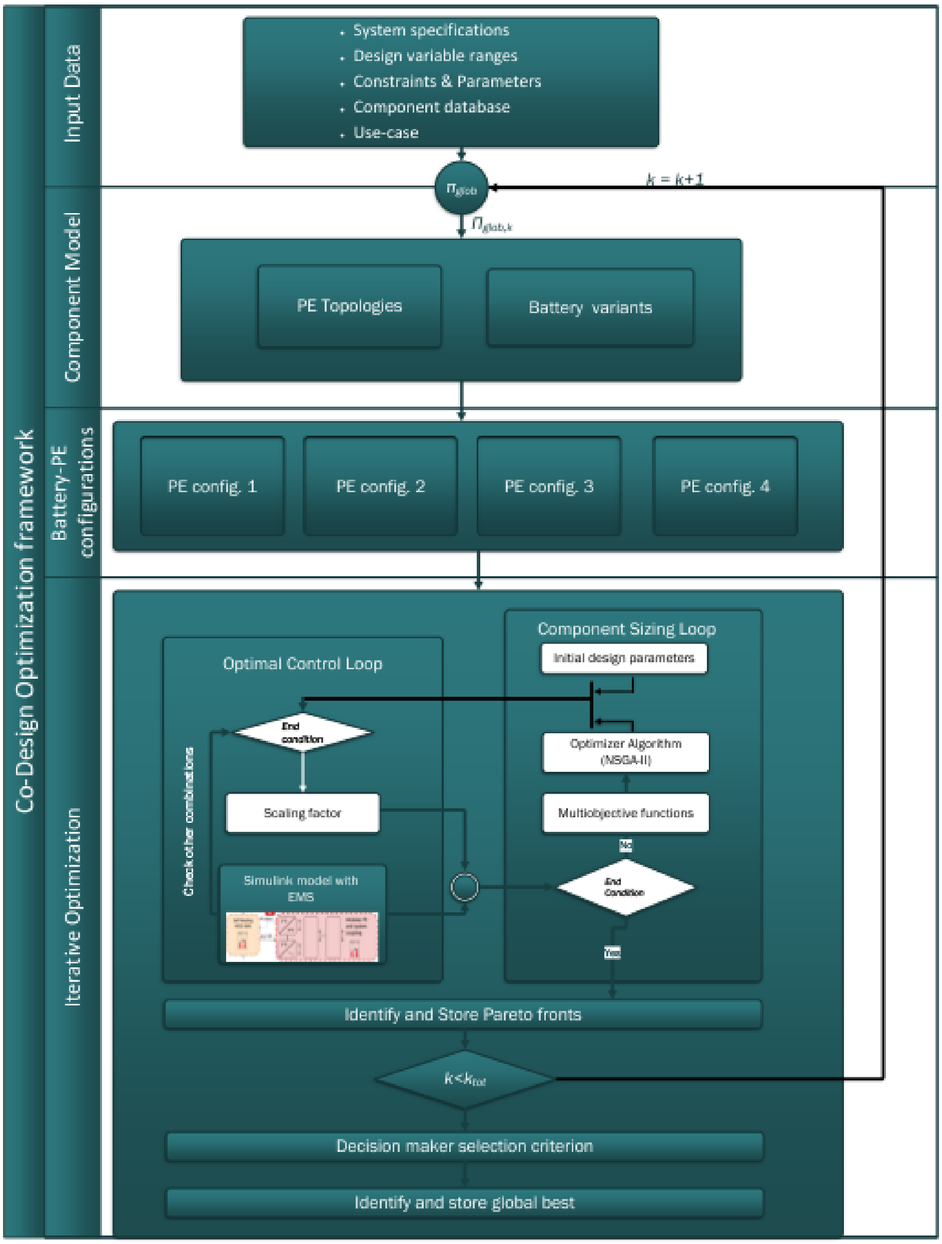


Figure 17 – Co-design optimisation framework architecture (iSTORMY) [13]

3.5 General multisector projects

3.5.1 FUTPRINT50

Start date: January 2020

End date: December 2022

Type of project: H2020 research and innovation program under grant agreement N° 875551

Project coordinator: University of Stuttgart (DE)

Summary: FUTPRINT50 was an EU funded collaborative research project set out to identify and develop technologies and configurations that will accelerate the entry-into-service of a commercial hybrid-electric aircraft. The aim was to develop promising modelling and simulation tools, innovative aircraft electrification technologies and a common roadmap for technology and regulation for this class of hybrid-electric aircraft. It focused on energy storage, energy recovery and the thermal management of hybrid systems. In addition to improving existing technologies, it will research and share an open-source tool for designing new hybrid-electric aircraft, hybrid-electric aircraft designs and reference data sets.

Main objectives:

- Provide an open reference for a 50-seat hybrid-electric aircraft configuration, including top level aircraft requirements, mission specifications and figures of merit.
- Develop innovative models, methodologies, open datasets and tools for evaluating the feasibility and multifidelity trade-offs of architectures and key technologies.
- Develop an open-source Common Research Model (CRM) for electrified aircraft and propulsion for the universal integration, benchmarking and assessment of future technologies, architectures, designs, models, and policies in the field of electrification.
- Develop energy storage models and pack solutions suitable for hybrid-electric regional flight up to TRL3.
- Develop propulsion related energy harvesting technologies up to TRL 4 and thermal management integration solutions and models up to TRL 3-4.
- Develop roadmaps for technology and regulation for a hybrid-electric regional aircraft and for future European demonstrators in this market segment.

Topics related to NEMOSHIP goals:

Technical topics: DT/tools, EMS/BMS, ESS integration in the vessel/vehicle/site, and ESS hybridisation.

Non-technical topics: training and dissemination activities, R&D gap definition, and contribution to new standard/regulations.

Project website: https://futprint50.eu/

The sections below summarise the topics, key learnings and challenges covered in the project and related to NEMOSHIP goals. In particular, the following topics are addressed: system model for designing process, ESS integration and hybridisation, energy management strategy, dissemination and training activities, R&D gap definition and Contribution to new standard/regulation.

System model for designing process

The propulsion system of an aircraft requires more specific and complex design or even optimisation methodology, to minimise the effect of uncertainty of the technology. For design, they use a methodology based on Set-Based Design (SBD), which generates as many configurations as possible for a later evaluation and discard the least desirable ones. The combination of this with the conversion of the non-filtered models into optimisation problems, is named Augmented Design and Optimisation (ADOPT). Additionally, this method is further developed by replacing the rule-based filtering of discardable configurations with a probabilistic one, the statistical surrogate model. This means that possible configurations with a probability under a previously specified threshold are discarded. The others are transformed into a multi-objective optimisation problem. The results obtained are then stored for post-processing.

For example, in the selected test case, there is a gas turbine and a motor driven by a battery combined through a gear box (Figure 18), and each component efficiency is specified. The simulation calculated the necessary power for each flight phase; in addition, the required fuel and battery mass can be specified. With the probabilistic model, more critical parameters are identified, which will be the ones with higher impact in the optimisation step.

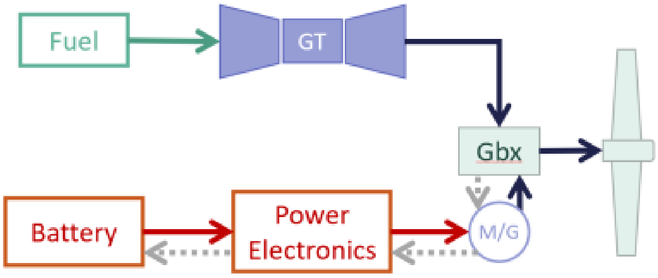


Figure 18 – FUTPRINT50 projects system configuration for design model [14]

ESS integration and hybridisation

In this project hybrid electric propulsion is proposed with several energy sources and power distribution paths. The objective is to reduce fuel consumption and maximise energy profitability, using the more suitable energy form for each stage of the operation. Specifically, in flight phases where most harmful pollution occurs.

HESS are also addressed. The possible combinations are between BESS, fuel cells and supercapacitors. This will depend on the architecture selection for the best EMS. This considers sizing, operation requirements, fuel/energy consumption and maintenance. Each component will be integrated to reduce the energy needed and optimise the utilisation of energy at each stage.

Energy management strategy

In this project the different EMS options have been compared based on the aircraft operational conditions (travel phases: take-off, climb, cruise, descent, landing) and selected generation architecture. The generation architecture can be composed of gas turbines, BESS, HESS, fuel cells and combinations. The objective is to optimise the available energy onboard. To that purpose, both design and operation processes are considered. For example, in terms of design, the addition of BESS increases the total mass of the system and thus, so does the energy consumption. This means that the optimum combination should be selected maximising the profitability during operation. Regarding operation of a mixed fuel-electric aircraft, using fuel first would result in a lighter aircraft with reduced thrust requirements when the electric energy would be used. As a solution, the project team proposes a multi-level optimisation approach.

For optimum operation, EMS is related to mission priorities and selected architecture. The objective is to minimise fuel or energy consumption, together with noise and emissions, making the operation flexible and reducing maintenance cost. At the same time, engine life will be extended improving efficiency.

The priorities will vary depending on the phase of the travel and the available traction components. The sizing also depends on these priorities, which could be 1) constant percentage of power/thrust, 2) constant amount of power/thrust, or 3) constant non-electric engine power. It may also depend on the requirements of the selected phase for which the sizing is being developed, such as on cruise or take-off. If the BESS capacity is low, using the energy stored during the descent phase may be more beneficial. However, electric energy can be also be beneficial in high power operations such as climb and take-off, to reduce fuel consumption, emissions, and engine degradation. So specific scenario for usage optimisation should be specified. Alternatively, different scenarios could be compared.

The Thermal Management System (TMS) will be part of the EMS and will tackle thermal energy reuse, energy harvest, intelligent use of heat sinks and thermal accumulators.

Training activities

The project team has included the FUTPRINT50 Academy (2021) in their training plans. Within that framework, engineering students are given the opportunity to develop their master thesis in collaboration with project partners, working on key topics for the project. This helps to develop knowledge and prepare future professionals for the sector. Key themes are: hybrid electric regional aircraft configurations, hybrid electric propulsion architectures, certification aspects for hybrid electric aircraft (HEA) and system architectures, sustainability from lifecycle to intermodal transport using HEA, systems integration for HEA, key technologies such as energy storage, energy harvesting, and thermal management, and design optimisation and decision-making for HEA. Finally, there is an aircraft design challenge, where students, in groups of five, designs a HEA according to CS-25 regulations, with the objective of minimising emissions and achieving a good balance between energy efficiency, complexity and performance.

Dissemination activities

The project has developed multiple disseminations materials such as articles, public deliverables, presentations, posters and videos. They have disseminated those through different activities, such as EASN International Conferences, scientific publications, EASN newsletters, and social media. The project has a YouTube, LinkedIn, twitter, and Instagram accounts, as well as a Research Gate and Zenodo profiles. There is also a project webpage where project-related information is available.

R&D gap definition

The project aimed to realise a systematic scientific analysis and modelling of the propulsion and power generation systems together with their integration. One of the objectives was to identify key-enabling technologies and technology gaps to be addressed. Generated aircraft or mission requirements, specifications and configuration definitions, as well as design methodology, will enable a techno-economic environmental risk analysis which will support the future roadmaps and direct R&D actions.

Additionally, the Y2040 conventional reference highlighted a couple of gaps to be addressed like getting good estimations on NO_x to assess the configurations against the TLARs.

Contribution to new standard/regulation

This type of aircraft should follow CS-25 regulation but a HEA is not fully addressed under it, which is a regulation gap. For example, a parallel architecture allows for a power boost in high load scenarios like take-off. Additionally, a serial architecture can increase redundancy or offers to replace a gas turbine with a battery pack if certification and technology requirements are met.

Considering novel propulsion concepts, a new definition of operation condition is necessary, as well as a propulsion architecture analysis. This may lead to consider interdependencies and redundancies of the system. Individual definition may be necessary due to the complexity of the HEA architecture in each system.

FUTPRINT50 worked on designing a roadmap for a regional HEA, both for key enabling technologies and related regulatory framework. Moreover, testing infrastructures will be defined, for hybrid-electric propulsion integration and power generation. If matched with the already existing infrastructure, it will lead to a concise roadmap for future standardisation and interoperability. The outcomes will benefit technological exploration, research infrastructures and regulatory policies.

Key challenges identified

- Technology development through the increment of efficiency leads to the integration of new electric/electronic equipment. This results in an increment in the supply power required, and thus the need for heat dissipation also increases. Additionally, electronics tends to miniaturisation, so the heat in each area is more concentrated. Consequently, TMS is key for the proper operation of the system.
- Complexity and uncertainty pose a significant challenge in the understanding of this propulsive technology.
- The major challenges of hybrid electric aircrafts are in the energy density of batteries, the thermal management of power train, the overall modelling of the subsystems and their interactions, and the identification of certification requirements.

Key learnings identified

Regarding the EMS, it is important to consider both the generation system architecture and the performance requirement in each travelling phase. This way, available energy can be optimised from both the design and operational perspectives.

By introducing probability and optimisation in the design model, the designer does not have to use experience to drive the design space exploration but instead uses data and encode their requirements. This allows the consideration of the unknown impact to the design process when new technologies are explored.

4 LC-BAT-11-2020 Projects

NEMOSHIP is an Innovation Action (IA) project awarded under the Horizon Europe topic “Exploiting electrical energy storage systems and better optimising large battery electric power within fully battery electric and hybrid ships” (HORIZON-CL5-2022-D5-01-01).

Since 2020, the European Union funded two Research and Innovations Actions (RIA) projects awarded under the Horizon 2020 topic “Reducing the cost of large batteries for waterborne transport” (LC-BAT-11-2020): SEABAT and CURRENT DIRECT.

Both topics have the same ambition to accelerate the deployment of large battery systems to improve the efficiency and to eliminate emissions from waterborne transport. More specifically:

- The call LC-BAT-11-2020 is focused on the development of cost-efficient batteries while addressing production process efficiency, certification requirements and methodology, as well as safety assessment. It first aims to speed up the transition of most short-range freight and ferry services towards zero emission.
- The call HORIZON-CL5-2022-D5-01-01, and the NEMOSHIP project, are focused on electrical architecture, optimal exploitation, and safe integration of large battery systems for a relevant number of ship types and operational scenarios. Both topics are therefore complementary, and connections should be logically established between projects to optimise their impact.

A public summary of the FLEXSHIP project also granted under the call HORIZON-CL5-2022-D5-01-01 is joined in Appendix D : FLEXSHIP sister project.

4.1 SEABAT Project

The overall objective of SEABAT is to develop a full-electric maritime hybrid concept based on combining modular high energy and high power batteries, novel converter concepts and production technology solutions derived from the automotive sector (Figure 19).

A modular approach will reduce component costs (battery, convertor) so that unique ship designs can profit from economies of scale by using standardised low-cost modular components. The concept is suitable for future battery generations and high power components that may have higher power densities or are based on different chemistries. The expected result is an optimal full-electric hybrid modular solution, reducing the oversizing and the TCO of maritime battery systems while minimising the battery footprint.

One of the main objective of NEMOSHIP is to develop and validate a modular and standardised battery energy storage solution enabling to exploit heterogeneous storage units. It will therefore be particularly interesting and efficient to build on the first results and conclusions of the SEABAT project to define the requirements of the battery system to be developed and validated in NEMOSHIP.

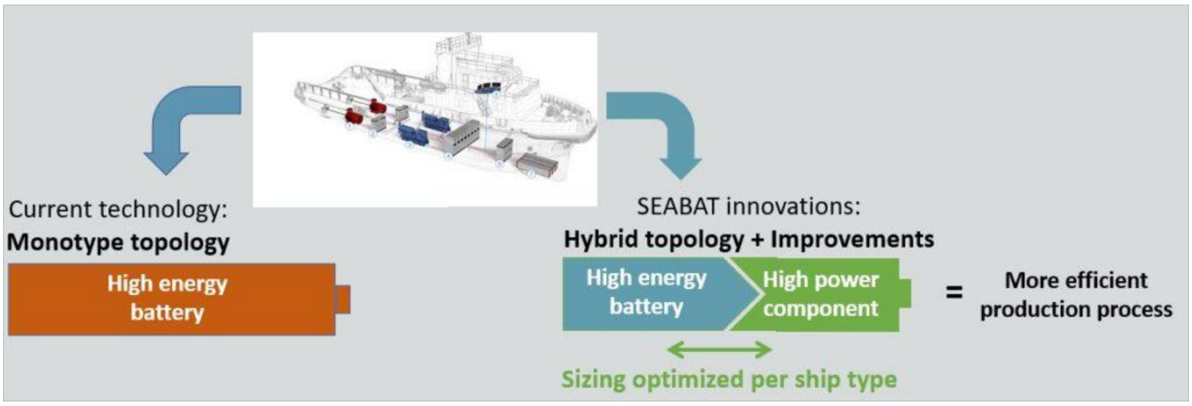


Figure 19 – SEABAT concept [15]

The following section highlights four key points addressed in the SEABAT project:

- Analysis of the requirements for marine batteries applications from a vessel perspective.
- Understanding of different types of battery technologies and designs.
- Analysis of the requirements for battery systems integration on board of a vessel.
- Evaluation of HESS topologies and system architecture definition.

4.1.1 Requirements for marine batteries applications from a vessel perspective

In the report “D2.1 Application matrix” [16], a methodology is proposed to define requirements for marine batteries applications focusing on the operational profile. This allowed determining the types of applications that can benefit from a HESS.

4.1.1.1 Methodology

The requirements for marine batteries can vary significantly for different types of vessels using the batteries for different applications (cf. Appendix C). The C-rates and number of performed cycles play an important role in designing a battery powered vessel. Each type of battery has a different combination of maximum C-rate and estimated number of cycles before the end of life of the battery cells. However, the operational requirements of most vessels do not exactly fit to the specifications of the marine battery systems available on the market. A common approach is to oversize the capacity of the battery system. This allows dealing with the highest required C-rates, the depth of discharge (DoD) is reduced for every cycle, which results in a longer lifetime of the batteries.

The concept of a HESS is considered to enable a more accurate sizing that fits the demands in C-rates and number of performed cycles of the vessel; this results in a better optimised battery system in terms of costs, weight or volume as well as fulfilling the lifetime requirements. To determine the types of applications that can benefit from a HESS, the types of vessels must be analysed based on their operational profiles and their operational requirements for batteries.

In total 34 applications have been gathered by the SEABAT partners with shipbuilding experience coming mainly from the largest demanding vessel types for marine battery systems (ferries, offshore support vessels, cruise & inland cargo vessels, fishing vessels, tugs, etc.). Then, a method to compare the types of applications based on their battery requirements has been proposed. This results in an overview of the different types of vessels and their application of batteries in a matrix.

4.1.1.2 Basic requirements and cycle definition

The basic operational requirements for batteries can be broken down into three parts: energy, power, and the number of cycles. Therefore, it should be determined how much energy in kWh is required for every operation, what is the maximum charge and discharge power (kW) required and how many cycles will be performed (daily or annually). The required power (kW) divided by the required energy (kWh) results in the C-rate (Figure 20). Typically, a certain battery technology is suited for one specific C-rate. Therefore, it is possible to reduce the complexity by comparing only two different variables, i.e., the maximum required C-rates and the number of performed cycles.

Analysis is based on available energy required, which for practical reasons and aging effects cannot be assumed to be 100 % of the installed capacity of the batteries. Therefore, the required energy is assumed to be 80 % of the rated installed battery capacity, which is used to define the C-rates as well as the performed number of cycles with a DoD of 80 %.

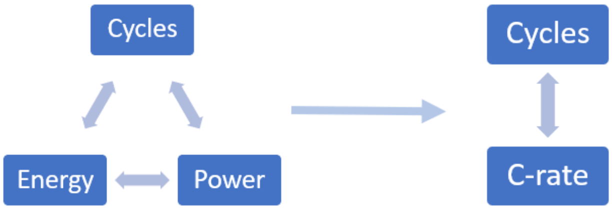


Figure 20 – Basic requirements for battery sizing and selecting [16]

The 34 battery powered vessels mentioned above have been analysed based on their operations from the point of view of the battery system to ensure that no difference is made with requirements for full battery electric vessels or Diesel-electric hybrid vessels. This is addressed by subdividing the different types of operations of a vessel in primary and secondary cycles (Figure 21Figure 21).

- Primary cycles are the most common types of cycles that a vessel will perform with the installed battery system, e.g., a ferry travelling between two ports. They represent the operational conditions at design level of the vessel.
- Secondary cycles are the operations performed outside of the average design conditions. For example, when the environmental conditions are out of the ordinary, when an emergency operation must be performed, or when the battery system is used for two different types of applications, such as load levelling and spinning reserve.

The battery requirements for the applications are based on the combination of both primary and secondary cycles. The goal of defining primary and secondary cycles is to find the right combinations of basic requirements (C-rates and number of performed cycles) and types of applications where a HESS can be beneficial for the overall battery system performance.

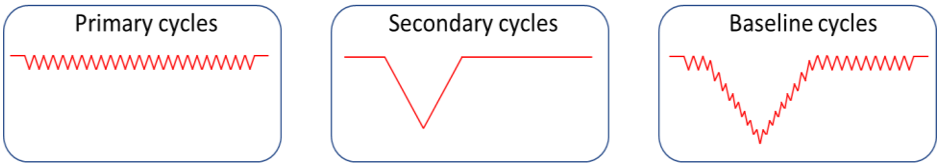


Figure 21 – Required power for primary, secondary and baseline cycles vs time [16]

4.1.1.3 Application matrix

The different vessels are evaluated for both C-rate and cycling requirements, and for both their primary and secondary cycles. The main goal is to create an overview of the different types of marine battery applications and to determine if it is possible to identify different clusters that have similar operational requirements regarding batteries. This overview is provided by an application matrix.

- **C-rate requirements**

The requirements from the primary cycles are higher than for the secondary cycles. 80 % of the primary cycles have a C-rate requirement below 6C, while 80 % of the secondary cycles have a C-rate requirement below 3C. This is mainly caused by the lower energy required for primary cycles, while the required power is often similar for both primary and secondary cycles. The C-rates requirements for the baseline cycles are equal to the C-rates of the secondary cycles (Figure 22).

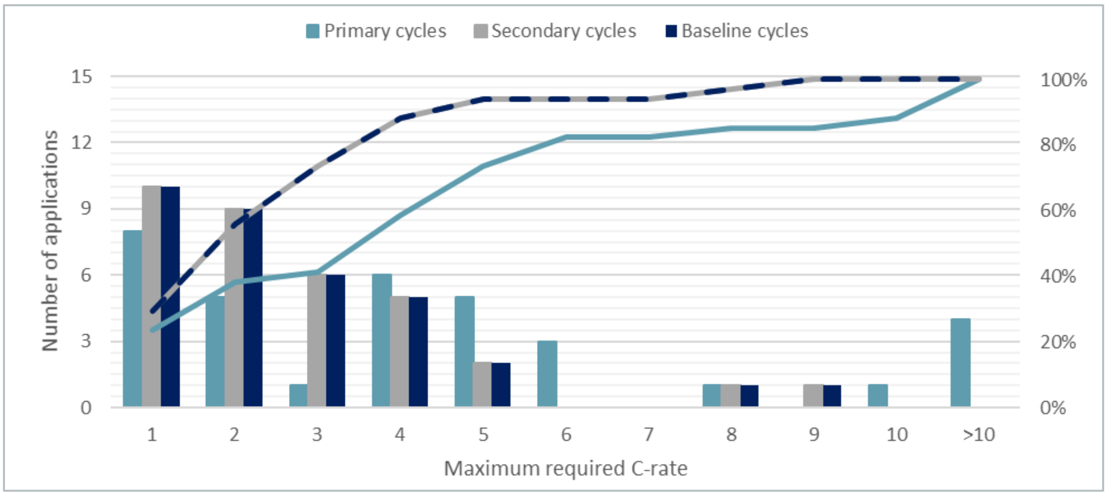


Figure 22 – Distribution and cumulative values for maximum required C-rates per application

According to the analysis of current marine battery systems in SEABAT Deliverable 2.2, the majority of the NMC and LFP based systems have a maximum C-rate between 1C and 3C. There are high energy batteries which typically have a maximum C-rate below or up to 1C. There are also several high-power battery systems that can go up to 6C, but above that the capabilities of lithium-ion batteries are limited. Therefore, 4 different types of C-rate requirements are differentiated (Table 7).

Table 7 – Battery technology classification by C-Rate (SEABAT)

Type	**A**	**B**	**C**	**D**
C-rate	< 1C	1C - 3C	3C – 6C	> 6C

- **Daily cycle requirements**

Approximately 30 % of the applications have a requirement to perform their primary cycles 10 or more times per day. For most lithium-ion technologies this can only be achieved by reducing the DoD and therefore oversizing the battery, resulting in inefficient use of installed battery capacity. These applications are therefore also considered as good candidates for a HESS, on the condition that a matching type of battery technology can be found.

The majority of the secondary cycles are performed less than once per day (Figure 23).

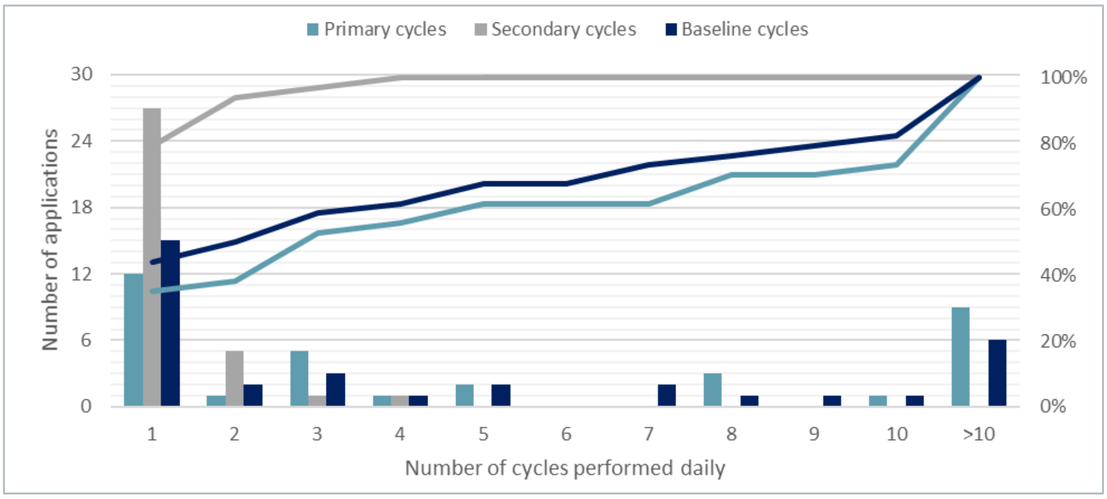


Figure 23 – Distribution and cumulative values for number of daily cycles per application

Marine battery systems currently on the market can perform between 3000 and 25000 cycles at 80 % DOD, 1C and 25 °C, based on the information provided by the suppliers as determined in SEABAT Deliverable 2.2, the KPI report. Where NMC and LFP battery types are in the range of 3000 to 10000 and LTO batteries go up to 25000. 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, based on 365 days per year, for LFP and NMC types of batteries. For LTO batteries this would be 2500 cycles per year, or 6.8 per day. Therefore, the cycling requirements are divided in four different groups (Table 8).

Table 8 – Battery technology classification by realised number of cycles (SEABAT)

Type	**A**	**B**	**C**	**D**
Cycles per day	< 1 cycle	1 – 3 cycles	3 – 7 cycles	> 7 cycles

- **Application matrix**

The figure below shows an overview of the main clusters and the performance of the marine battery systems currently on the market. Based on the evaluation of batteries technologies available on the market, the maximum continuous discharge C-rates, and the number of estimated cycles per day is shown for the 3 main battery types: high energy (HE), medium energy (ME) and high power (HP), as shown in Figure 24.

There are two main groups of applications, AA (24 %) and BA (21 %) that require one or less cycle per day and could be achieved with single requirements (C-rate or number of cycles). The results point out the opportunities for high energy battery systems with low cycling capability, a type of battery system that is not common on the marine battery market currently. At the other end of the spectrum about 20% of the applications have some kind of combination with CC, CD, DC, or DD type of battery requirements with relatively large C-rates and a large number of cycles. Battery systems using LTO cells for example are assumed to be a good match for these applications, but there are not many marine battery systems which make use of this technology yet.

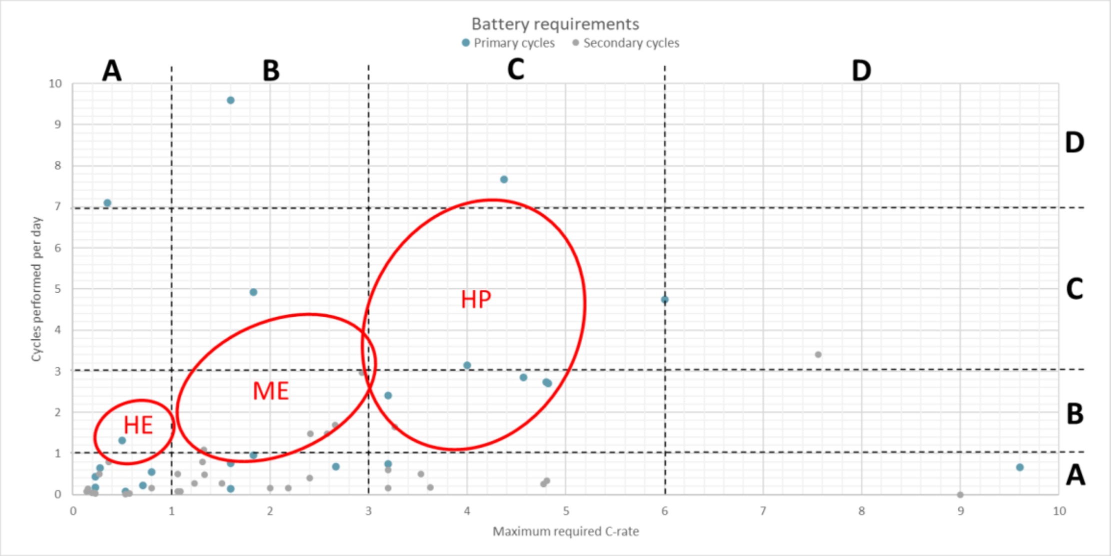


Figure 24 – Overview of application types based on basic battery requirements and current marine battery types (HE=high energy, ME=medium energy, HP=high power) [16]

4.1.1.4 Feasibility for hybrid battery systems

The feasibility for a hybrid battery system is determined by assigning a score for each application based on the multiplied difference between the C-rate requirements and the cycling requirements for the primary and secondary cycles. A high score is assumed to to indicate the feasibility of the application as a use case for a HESS.

$$\left(\begin{array}{c} |Primary\ C\text{-}rate - Secondary\ C\text{-}rate| \\ * \\ |Number\ of\ primary\ cycles - Number\ of\ secondary\ cycles| \end{array}\right)$$

The analysis has shown that two vessels which use the battery system for different types of battery applications, for example as a peak shaving and spinning reserve application, are identified as the most feasible application for a HESS. However, this is not the case for all vessels that use their batteries in similar combinations of applications. Nevertheless, the aim of the SEABAT project is to design a HESS for a fully battery powered vessel and most applications which combine different types of battery applications have a hybrid propulsion system. The fully battery powered vessels that showed most compatibility with a HESS are ferries with a relative high number of cycles as their nominal operation, but with additional energy requirements for the batteries under certain circumstances.

The main conclusion from the application matrix is that ferries and tugs are the types of vessels which are most likely to benefit from a HESS. In some particular (hybrid) cases, fishing vessels are an interesting candidate as well. The main reason for the ferries and tugs to be interesting for a HESS is the fact that these types of vessels usually have a primary cycle which is relatively small compared to their overall energy requirement and which is performed a relatively high number of times per day. Additionally, C-rate optimisation can be a great asset for HESS application for vessels that have a C-rate requirement that does not match the specifications of most battery systems and therefore will require oversizing of the batteries in a monotype battery system situation.

4.1.2 Evaluation of battery technologies and designs

The report “D2.2 Key Performance Indicators list” [17] analysed the performance of 30 marine battery systems from 15 different suppliers based on nine different groups of properties: costs, energy, power, lifetime, thermal management, safety, mechanical integration, electrical integration, and the battery management system. In total 33 different battery properties are used to determine the overall score of the battery systems and analyse them according to the design and chemistry.

4.1.2.1 Battery system designs

There are four main types of battery system designs identified as shown in Figure 25.

Module based systems is composed of modules which can be placed individually and do not require a fixed racking system. Each module has a certain output voltage, and the system voltage can be varied by connecting modules in series. Module based systems are in general flexible considering installation in relatively small battery spaces or on smaller types of vessels.

Tray based systems are mainly seen in the automotive industry. Most of the marine tray-based systems come from the automotive industry originally and have been marinised to receive a marine type of approval. A tray-based system usually comes with a standard output voltage, and they are not designed to be connected in series with each other.

Rack based systems have predefined racking solutions for their battery modules. Each rack can be placed individually in a battery space. In most racking systems the additional safety measures and cooling systems are integrated. Rack based systems can have some level of flexibility in their design but are mainly bound to specific standard sizes.

Block based systems are designed to reduce the required service space as a benefit for larger types of vessels. These types of systems are usually outfitted systems which facilitates integration on board if there is enough space available. Some block-based systems consist of multiple racks combined, but in contrary to the rack based systems, these racks cannot be placed in a battery space individually.

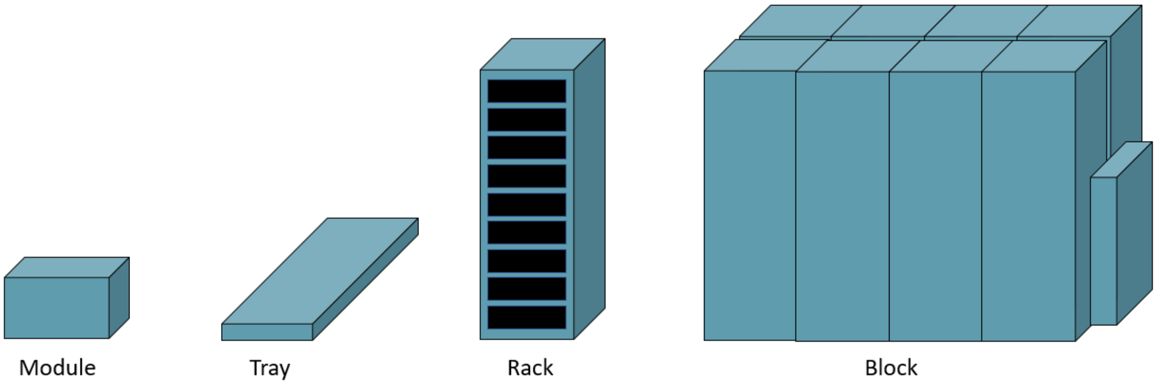


Figure 25 – Different types of battery system design [17]

4.1.2.2 Methodology: KPI analysis

The KPI analysis consists of four steps:

1. Identify the battery properties used to determine the performance of a battery system.
2. Analyse existing marine battery systems based on each property.
3. Define a rating system based on the score for a specific property from 1 to 5.

4. Calculate the performance based on the requirements of different vessel types.

The battery properties, classified in nine different groups, are shown in Table 9.

Table 9 – Battery design properties (SEABAT)

Cost	
System costs	The costs for the basic battery system without considering the costs for installing it on board of a vessel. The system costs are usually expressed in €/kWh.
Cycle costs	The cycle costs consider the expected lifetime of the batteries. The system costs are divided by the total expected energy throughput in kWh, calculated by the estimated number of cycles at 80% DoD. This will also result in a €/kWh price, but then per cycled kWh instead of installed kWh.
Energy	
Gravimetric specific energy	Refers to the energy per installed weight in Wh/kg, based only on the battery system itself and not on auxiliary equipment.
Volumetric specific energy	Refers to the energy per installed volume in Wh/L, based only on the battery system itself and not on auxiliary equipment, and without considering the required service space around the battery system.
Cell to module weight ratio	The ratio between the weight of a module and the weight of all the cells inside the module combined. This provides information about the efficiency of the design of the module considering weight.
Cell to module volume ratio	The ratio between the volume of a module and the volume of all the cells inside the module combined. This provides information about the efficiency of the design of the module considering volume.
Power	
Gravimetric specific power	In W/kg based only on the battery system itself and not on auxiliary equipment.
Volumetric specific power	In W/L based only on the battery system itself and not on auxiliary equipment, without the required service space around the battery system.
discharge C-rates	Maximum continuous discharge C-rates.
charge C-rates	Maximum continuous charge C-rates.
Lifetime	
Cycles	The number of cycles that can be performed at 80% DoD, at 1C and 25 °C.
Maximum design life	depends on multiple variables such as temperature, number of cycles, depth of discharge and C-rates, but is usually determined at approximately 10 years for most types of battery powered vessels.
Thermal management	
Heat rejection	The required cooling capacity according to the percentage heat rejection at a 1C discharge rate.
Inlet temperature	The required inlet temperature of the cooling medium.
Safety	
Cell chemistry	The materials used for the battery cells determine the thermal stability of the cell.
Thermal runaway propagation	Evaluated considering propagation isolation measures at module and/or cell levels
Gas release	The amount of gas that is release in case of thermal runaway (@ 25°C / normal atmospheric pressure).
Ventilation system	The method of ventilation required in the battery space.
IP rating	Impacts the type of firefighting system to install in the battery space.
Mechanical integration	
Smallest building blocks	The smallest part which can be placed individually and independently of others (function of battery system design).

Height optimisation	The ability of a battery system to optimise the usage of the available height in a battery space.
Service space	The required service space for installation and maintenance, in percent of the required floor surface of a battery system.
Electrical integration	
Maximum voltage	Maximum voltage
Voltage window	The voltage window is determined by the difference in percentage between the voltage at 100 % and at 0 % SOC.
Voltage range	Range of the minimum and maximum for nominal voltage.
Voltage step	Voltage step at which the nominal voltage can vary in range.
Power connections	The installed capacity in kWh per power connection is analysed by comparing the embedded energy per battery module.
Battery Management System	
BMS architecture	Rated on: the number of strings that can be connected in parallel per BMS, the power consumption per BMS and the internal redundancy of the BMS.
Cell balancing	Rated on: active or passive balancing, automatic or manual start, and balancing accuracy in mV.
BMS sensors	Rated on: the number of cells per voltage sensor, the number of cells per temperature sensor and if the battery system has an integrated thermal runaway exhaust gas sensor.

4.1.2.3 Battery performances

The battery system performances were calculated based on the KPI rating system as described in the methodology. First, an overview is provided with equal weighting of all categories. The results are shown for the different cell chemistries and for the different types of system design.

Figure 26 shows the comparison of the costs per cycled kWh and the overall performance score of all battery systems based on the used cell chemistry. The highest scoring battery systems have LTO cells, with an average score of 3.5. The systems based on NMC cells have an average score of 3.0 and the systems based on LFP cells have an average score of 2.7. Additionally, the systems with the lowest costs per cycled kWh are either based on LTO cells or NMC cells.

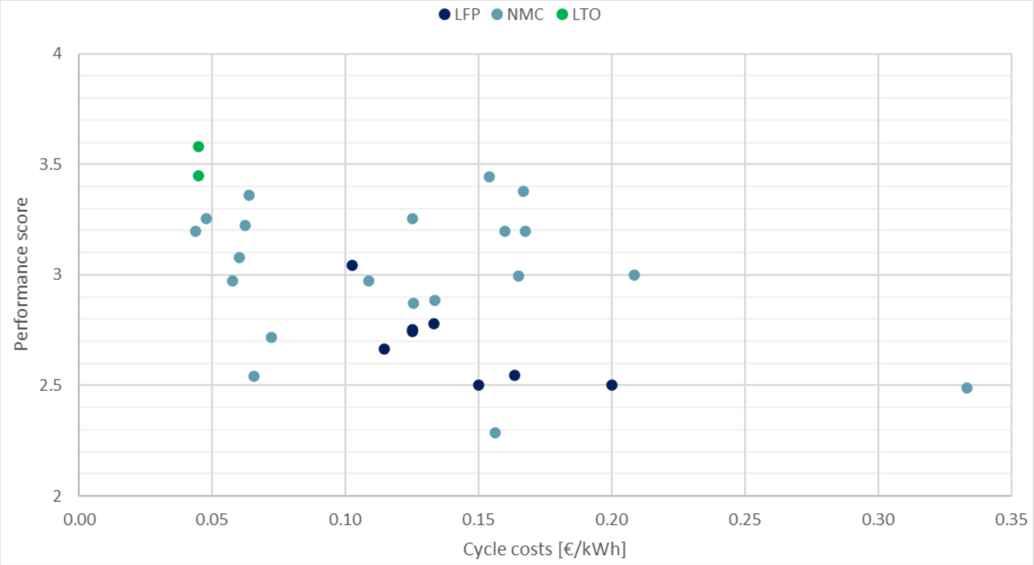


Figure 26 – Costs per cycle compared to battery performance for different cell chemistries

The analysis of the overall performance score of all 30 battery systems is shown in Figure 27Figure 27. The average performance score for all battery systems combined is 3.0. The lowest scoring battery system has an overall performance of 2.3. The highest scoring battery system has an overall performance of 3.5. The tray and rack-based battery systems have the highest average scores of 3.1

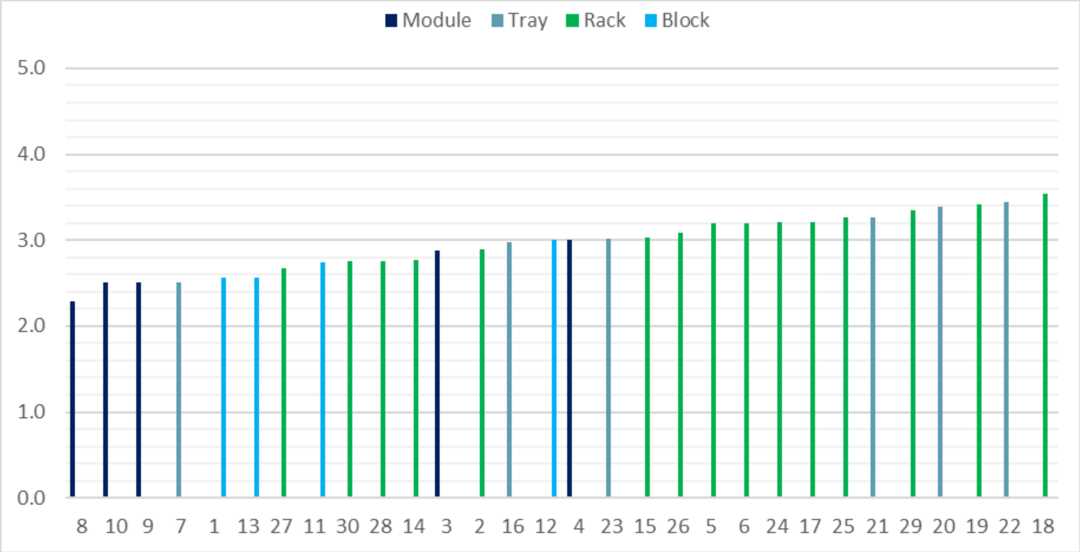


Figure 27 – Overview of overall performance score per battery system

In the report, the scores are also given with varying weighting factors between categories to increase the importance of one category and to show which systems perform better when different requirements play a more important role in the design of the battery system. This detailed analysis made it possible to draw recommendations for the design of HEES system.

4.1.2.4 Recommendations for HESS concept design

The focus for the design of the HESS system should be on a high energy and a high-power system. An overall medium energy battery system can be created by the HESS concept by combining the high energy batteries with the high-power batteries to fulfil the requirements of the vessel.

The recommended system design is either a rack-based system or a tray-based system. The rack-based systems have the most stable performance scores on all different categories. It is then recommended to focus on developing a versatile design with a high energy density which results in a versatile and all-round applicable system. However, the highest performance on energy and power density can be achieved with a tray-based system design. In this case, the focus should be on safety performance, electrical integration flexibility while keeping the costs for the system relatively low.

Regarding **costs**, the high-energy battery system should have a system cost around 400 €/kWh and cycle costs around 0.07 €/kWh. The high-power battery system have a system costs around 510 €/kWh and cycle costs around 0.04 €/kWh. This is only considering the costs for the battery system without any power conversion. However, none of the existing systems has power conversion included and therefore the requirements for this cannot be defined based on the current systems.

The gravimetric **energy density** of the high-energy battery should be around 180 Wh/kg and the volumetric energy density should be around 270 Wh/L. For the high-power battery system, this should be around 90 Wh/kg and 120 Wh/L. However, the energy density of the complete battery room should be taken into account in the design choices of the battery system as well. Therefore, the smallest building block of the battery system should not be too large, preferably below 100 L. Finally, the required service space around the battery system should be minimised. A required service space below 40 % of the footprint of the battery system is considered as the highest score on this topic.

The gravimetric **power density** of the high-energy battery should be around 280 W/kg and the volumetric power density should be around 400 W/L. For the high-power battery system, this should be around 700 W/kg and 1000 W/L. Besides this, the maximum continuous C-rates for these batteries should be around 1C for the high-energy battery and around 5C or higher for the high-power battery.

Concerning **cycle lifetime**, most marine battery systems displayed a 10-year lifetime. In general, the high-power batteries need to be cycled more compared to the high-energy batteries. Therefore, it is recommended to aim for a cycle life above 16000 cycles at 80% DoD for the high-power batteries and above 5000 cycles for the high-energy batteries. It is also important to consider the possibility to replace only battery modules at their EOL and not overall tray/rack.

The **thermal management system** should be able to cool the batteries as efficiently as possible. A heat rejection below 0.5% of the discharge power at 1C is considered the highest score, and below 1.5% is considered above average. Having a required inlet temperature of the cooling medium around 25°C is preferred; a value between 22°C and 25°C is considered above average performance.

Regarding **safety of the battery system**, it is recommended to have cell level thermal runaway propagation measures and an integrated gas exhaust ducting. This will reduce the complexity of the integration of the system on board of a vessel. The most important purpose for a fire extinguishing system in a battery space is the ability to cool, to prevent the fire from igniting the batteries. A water mist fire extinguishing system is assumed most effective in achieving this and then the battery system should have a minimum IP rating of 56, but preferably an IP rating of 67.

Regarding **electrical integration**, the output voltage of the battery system should at least be able to supply a 700 Vdc and 1000 Vdc fixed DC-bus. However, for higher flexibility and applicability to different types of electrical systems on various ship types, it is preferred to be able to adjust the voltage range of the battery system. A maximum nominal output voltage of 1000 Vdc is considered above average, 1258 Vdc or higher results in the highest score. A voltage range of 812 Vdc is considered above average. Above 1000 Vdc is considered as the highest score. A voltage step below 59 Vdc is considered above average, 10 Vdc or lower is considered as the highest score. The capacity per module of 20 kWh is above average, 50 kWh per module or higher results in the highest score.

The **battery management system** is preferred to be able to manage an unlimited number of strings in parallel - more than 12 is considered above average. The BMS should have a power consumption of 0.63 W per installed kWh to perform above average and it should have an integrated redundancy function. The balancing of the battery cells should preferably be done actively and the process should be started automatically. A balancing accuracy of 7.5 mV is considered above average, and 1.5 mV is considered as the highest performance. Each battery cell should have at least 1 voltage sensor, 2 sensors would be optimal for redundancy, and one temperature sensor for every 4 battery cells. An integrated gas detection sensor is considered as a strong point, as this improves the safety and the ease of integration on board of the vessel.

Finally, it must be noted that the analysis of current marine battery technology has been performed without taking power conversion into consideration. However, power conversion will be an important topic in the final design of the HESS, and this will need to be considered in the comparison of a monotype battery system and the HESS to identify the actual possible benefits of a HESS.

4.1.3 Requirements for battery systems integration on board of a vessel

The report “D2.3 Detailed requirements document” [18] analyses the current regulations in different classification societies (Bureau Veritas, DNV-GL, RINA, Lloyd’s Register) and draft some guidelines aimed at expanding the international requirements and promoting the adoption of a single set of regulations and/or standards.

4.1.3.1 Overview of classification society rules

There are currently no international standards for marine battery installations. However, the International Electrotechnical Commission (IEC) is working on standards 62619 and 62620. Some additional requirements are available for transportation of batteries (e.g., UN 38.3 Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria).

Classification societies, upon their experience, may have developed specific rules and/or additional class notation supplementing these international regulations. As a summary, this section presents the current situation on ship battery regulation considering five classification societies (Table 10).

Table 10 – Current situation on ship battery regulation (SEABAT)

Society	Existing rules
Bureau Veritas (BV)	In 2017, BV has launched a new series of notations and rules addressing the requirements of energy storage systems (ESS) to support ship operations in reducing emissions. The new rules and notations aim to provide a framework for electric and hybrid power solutions, with the notations covering power management (PM), power back-up (PB) and zero emission (ZE) standards. They are included in the following regulations: • NR467 STEEL SHIPS – January 2021 edition • NR566 SHIPS LESS THAN 500GT – July 2018 edition • NR217 INLAND NAVIGATION VESSELS – February 2019 edition • NR500 YACHTS – January 2016 edition
DNV-GL	**Electrical installation**: The requirements about battery system design, protection and installation, relative to all ships, regardless of whether they belong to any specific batteries class notation, are included in Part 4 (System and Components), Chapter 8 (Electrical Installation) of DNV-GL Rules, edition July 2020. **Class notation Battery**: Since the October 2015 edition, the DNV classification society has been developing a class notation for the use of batteries in ship propulsion. The additional class notation Battery facilitates the use of electrical energy storage (EES) installations on electric and hybrid vessels. The requirements are presented in Part 6 (Additional Class Notation), Chapter 2 (Propulsion, Power generation and Auxiliary system) on DNV-GL rules. These Rules cover design, installation and certification requirements for lithium-ion battery systems and electrochemical capacitor systems. **Guideline for large maritime battery systems**: Apart from current regulations, DNV-GL has a guide applicable to large marine battery systems. The aim of this guideline is to help ship owners, designers, yards, system and battery vendors and third parties in the process of feasibility study, outline specification, design, procurement, fabrication, installation, operation and maintenance of large Li ion-based battery systems. These guidelines are consistent with the DNV rules for battery power.

RINA	In RINA Rules, specifically in Part C (Machinery, system and fire protection), requirements and characteristics about propulsion with batteries are present in the following items: • General requirements of electrical installation (system design, protection, storage, location and installation). Refer to RINA Rules, Pt C, Ch.2, Sec.3, 7, 11 and 12, edition January 2021. • Battery powered ships. Refer to RINA Rules, Pt C, Ch.2, App.2, edition January 2021. • Additional class notation HYB-… Refer to RINA Rules, Pt F, Ch.13, Sec.28, edition January 2021. RINA Rules develops in Part F (Additional Class Notation), Chapter 13, Section 28 the additional class notation **Hybrid Propulsion Ship** (HYB-…), assigned to ships equipped with a hybrid propulsion system.
Lloyd's Register (LR)	**Regarding batteries**: Part 6, Chapter 2, Section 12, of the Lloyd's Rules for Classification of Ships (edition July 2020) is dedicated to the requirements that must be applied in case of installing batteries on board. It defines the additional class notation **Hybrid Power and Hybrid Power (+)**. Also, LR developed in 2015 the Guidance for Large Battery Installations. **Hybrid electrical power systems**: Based on Lloyd's Register Rules, Part 6, Chapter2, Section 24 (edition July 2020), the requirements of the section 24 are applicable to ships having a main source of electrical power which is provided by hybrid electrical power generation and distribution systems within which the main electrical power demand is supplied by two or more different types of power source or by electrical energy stored (main emergency source). **Guidance for large battery installations**: LR's experience with large battery installations is captured in this guidance document aimed at facilitating a risk-based approach to battery use. The guidance describes the key hazards to consider when installing battery technology, and gives an overview of non-prescriptive approach to approval. The guidance also covers battery chemistry and industry standards.
American Bureau of Shipping (ABS)	The Classification Society American Bureau of Shipping (ABS) started developing regulations regarding ship batteries a few years ago and started developing the requirements in the **Rules for Building and Classing Marine Vessel** in the Part 4 Vessel System and Machinery, in particular in Chapter 8 Electrical System. In 2017, ABS developed a specific class notation for ships using lithium batteries as propulsion ESS-LiBattery. This **Rule is the Guide for Use of Lithium Batteries in the Marine and Offshore Industries**. In 2020, ABS developed the **Guide for Hybrid Electric Power Systems for Marine and Offshore Application**. The guidelines focus on systems integrating electric power generation and storage technologies with conventional power generation. The guide also introduces a new class notation **Hybrid IEPS**.

4.1.3.2 Regulatory analysis & guidelines

From the analysis of the current regulatory framework, one objective of the SEABAT project is to provide guidelines applicable to the functional design and certification of battery installations on a life-cycle perspective. The results may be proposed to the Industrial Automation and Control System (IACS) as Unified Interpretations, or be forwarded to the IMO, or to standard organisations (e.g., ISO), as appropriate.

The analysis of the requirements and limitations of the existing battery regulation in different classification societies focuses its content on the following aspects:

- Identify the current framework - regulations, rules, guidelines, codes, and standards - applicable to battery installations in vessel design, construction, and operation.

- Provide references for the correct and safe design, testing and certification of battery installations during the project.
- Evidence regulatory gaps or barriers which may limit the full potential of battery installations.

The analysis of the class requirements for battery installations shows that the terminology used is not always identical, but in general the following key sections are covered and adopted for the regulatory review:

- General – Application
- Design and construction
- Definitions and acronyms
- System design (safety) requirements
- Location
- Installation
- Battery spaces
- Battery chargers
- Battery Management Systems (BMS)
- Availability of power
- Control, monitoring, alarm, and safety systems
- Risk assessment
- Thermal management and ventilation
- Testing, surveys, and inspections
- Certification process
- Operation and maintenance
- Operational conditions and requirements

In this review, reference is made to the most used and known rules, regulations, standards issued by the major classification societies and authorities. The structure selected for this review is a set of spreadsheets, clustered according to a logic thematic breakdown, supplemented by specific comments and considerations. This solution is preferred to evidence the regulatory gaps in contrast with well-regulated (or even over-regulated and too prescriptive) requirements. This structure is also suitable to progress with the activities scheduled in other tasks, using the spreadsheets as a baseline in the project. Based upon the gaps and lessons learnt in the project, this baseline will be updated in due course with performance criteria and project guidelines for future functional design and certification of battery installations on a life-cycle perspective.

4.1.3.3 SOLAS regulations and fire safety

Apart from the conventional lead battery installations for the emergency source of power, IMO and IACS provisions do not cover exhaustively with statutory requirements the following aspects for any type of battery installations:

- Structural fire protection of battery installations.
- Active fire protection systems of battery installations.
- Risk assessment criteria (e.g., safety margins, fire hazards, acceptability criteria, individual/societal risk of passengers/crew/firefighters, fire risk control options, etc.).
- Fire detection systems of battery installations.

- Battery installation normal and emergency cooling systems.
- Ventilation systems of battery cells and gas exhaust.

However, the **SOLAS Convention specifies minimum standards for the construction, equipment and operation of ships, compatible with their safety**. The chapter II-2 is about fire protection, fire detection and fire extinction. The goals and functional requirements are explicitly mentioned through 23 regulations based upon the fire safety objectives:

- Prevent the occurrence of fire and explosion.
- Reduce the risk to life caused by fire.
- Reduce the risk of damage caused by the fire to the ship, its cargo, and its environment.
- Contain, control, and suppress fire and explosion to the compartment of origin.
- Provide adequate and readily accessible means or escape for passengers and crew.

The Fire Test Procedures Code 2010 as amended (FTP Code) is applicable for products which are required to be tested, evaluated, and approved under SOLAS. The relevant maritime administration is tasked to evaluate the submission, in accordance with the relevant IMO guidance. However, there is no mention of battery installations in the FTP Code. Test methods are currently limited to (non-combustible) materials for bulkheads, decks, ceilings, doors, windows, etc. as well as other components e.g., thermal, and acoustic insulation materials, fire dampers, cable and pipe penetrations, ventilation ducts etc., considered to be directly related to fire protection.

As a result, **some aspects of fire and explosion risk would require further evaluation for marine batteries installation**. It is therefore important that the approach used to assess safety can properly describe the effects on fire safety posed by the battery installation design and arrangements. The difficult part is to identify and evaluate uncertainties, with sufficient confidence to establish appropriate safety margins. Moreover, the focus on safety of human life in the fire safety objectives makes it topical to address not only the safety of passengers, but also the safety of firefighters and crew – which is a broad concept difficult to translate into prescriptive requirements.

Beside the combustibility assessment, it is nevertheless important to identify ignition sources and ensure that battery installations integrity is properly protected by fire insulation. As long as the construction is thermally protected, battery installations will not add to the generation or toxicity of the produced smoke. But, in the event of a fire lasting long enough to involve the structural divisions, an increased fire risk and toxicity of smoke could occur. This toxicity depends on the type of batteries. It is therefore crucial that fire hazards introduced in case of a long-lasting fire (i.e., lasting for more than 60 minutes), as well as the effects of fire extinguishing systems, are carefully addressed in the SOLAS regulation II-2/17 assessment. Even if not explicitly mentioned by prescriptive requirements, it may prove necessary to better address the fire functional requirement by a combination of passive and active measures, e.g., by an additional active fire-extinguishing system on exterior surfaces, or additional structural fire protection to mitigate the fire risks.

Direct fire safety assessments are usually based upon fire models and CFD computational tools. Critical aspects of such models include the verification of the effects fire extinguishing systems on a fire, and their possible contribution to prevent major consequences.

The way out to progress on fire safety of battery installations could be found in a new integrated performance-based methodology, following a fire safety engineering approach to meet SOLAS objectives and functional requirements - e.g., probability of ignition, risk by toxic product and smoke, smoke containment, structural integrity, etc. Specific considerations would be required on:

- Standards and acceptance criteria for fire resistance test procedures.
- Standards for fire protection effectiveness.
- Standards for fire detection and firefighting.
- Life-cycle performance criteria for fire safety.

4.1.3.4 Conclusion about regulation requirements

As a **general consideration**, the current regulatory framework applicable to the marine battery installations is the result of a fragmented approach, with prescriptive rules, codes and standards developed on rather conservative principles. Rules often refer to traditional battery cell solutions and construction techniques, despite the impressive rate of technology growth in other industrial sectors. This may be a barrier to the uptake of solutions based on new battery cells and technologies.

Likewise, a performance-based approach, including risk assessment and technology qualification processes to verify if the battery installations are “fit for purpose” may result in complex and time-consuming activities slowing down the exploitation opportunities on large marine applications. The possible way forward is found in a balanced use of prescriptive regulations and risk analysis where required, supplemented by performance assessment methods, computational tools, and models. This may offer a way around the lack of operational experience on new technologies.

In general, all class societies have requirements on certification, factory and onboard tests and require manuals for maintenance and operation. In addition, DNV requires instructions for emergency operation. In general, tests on batteries are based on IEC 62619. All class societies require risk assessment, to evaluate the measures to be adopted to minimise the risks associated to the use of lithium-battery system and their installation on board of ships.

About **thermal management**, two methods can be acceptable: direct cooling or ventilation of the battery spaces as far as direct cooling of the battery system is not currently mandatory. The risk related to the use of direct liquid cooling should be considered: only DNV considers the risk of a cooling liquid leakage inside the module to avoid the risk of off gassing from the module. Without direct cooling, the ventilation of the space becomes very important. Not all class societies impose mechanical ventilation, which should be required providing clear requirements about performances, types, sizing and ducting in relation with other spaces on board. It is important to note **that ventilation is also necessary for the extraction of gasses following a thermal runway**.

The **installation of a gas detection is not considered mandatory by all class societies**. For RINA and DNV the installation is in relation to the battery chemistry, taking into consideration the gases (flammable/toxic gases) which may be emitted by the battery system. For ABS the installation of a gas detection is mandatory with automatic disconnection of the battery system if the concentration of gas in the battery space reaches 30% LEL. The rules do not clearly specify where gases, which may be emitted from the battery system in the event of a fault, are to be released. **Only DNV Rules cover the matter with specific requirements**, in case of gases released into the battery space, and EES systems installed in enclosed cabinets with an integrated off-gas ventilation duct.

In general, lithium-battery spaces are not considered as hazardous spaces, since in normal operation there is no release of gases. But DNV Rules include specific requirements for the space considered as hazardous area in relation to the flammable/toxic gases released following a failure of the EES system.

Other aspects of the battery spaces are different, e.g., RINA requires self-closing doors, ABS gas-tight doors or self-closing gas-tight doors with no holdback arrangement only if battery space is located adjacent to and within machinery space of category A, DNV requires normally closed doors with alarm or self-closing doors.

What is common to all class societies is the request to have two independent battery systems located in two independent battery spaces when the ship main source of power is based on lithium-batteries.

The structural fire protection category of the space depends on the class societies, but mainly define the space as a "machinery space" and require that the safety systems to be at least equivalent to those of a machinery space of category A.

For fixed **fire-extinguishing system** in battery spaces, different requirements have been issued. While RINA, ABS, BV require a system in relation to the battery manufacturer instructions and, as consequence, appropriate to the battery chemistry (e.g., powder, or gas based, or water-based fixed fire extinguishing system), LR and DNV strongly recommend a water-based fixed fire-fighting system, due to its inherent heat absorbing capabilities.

In terms of **construction requirements**, all class rules are in general aligned, except for the degree of protection (IP) which is a very important matter, e.g., in case of risk of flooding in relation to the installation of the batteries. Other construction requirements have been considered, such as the design of the module to prevent propagation of a thermal event, flame retardant materials, pressure relief valve of the casing of a cell, module, battery pack and battery systems, as well as the request to have an emergency shutdown device independent from the control system and located outside the space and on the navigation bridge for batteries serving propulsion.

4.1.4 Evaluation of HESS topologies and system architecture definition

The two SEABAT deliverables addressed in this section are confidential. As part of the clustering dissemination actions, the SEABAT coordination team will be contacted to discuss in more detail, depending on the technical orientations taken in the NEMOSHIP project, whether certain results can be exchanged.

4.1.4.1 Evaluation and selection of architectural concepts

In the report "D3.1 Evaluation and selection of architectural concepts" [19]**,** three topologies are detailed, evaluated, and compared towards a baseline state of mono-type battery topology regarding system cost, mass, and volume, electrical losses and required amount of components.

The HESS topologies that are investigated in this work are based on the following concepts:

Topology 1: Converter integrated into the battery modules, transforming the module into a controllable voltage source. The integration requires balancing compactness and heat load versus efficiency and cost. This topology scores on average on all points better than the baseline battery pack. It has the most advanced models for the different systems. However, it uses the same approach and input requirements as the other topologies.

Topology 2: Switching between individual cells to achieve e.g., a near-constant DC voltage. The switch needs to be developed for robustness and efficiency, together with the proper control. It scores on average higher on volume, weight and amount of components when comparing to the baseline. Assigning a switching device to multiple cells is a possible solution to improve the size and cost.

Topology 3: Partial power converter integrated into the battery modules where existing concepts need to be upscaled to MWs, developed for bidirectional flow (charging and discharging) and integrated with (over)voltage protection circuits. It scores on average equal to the battery pack volume. One major improvement for this topology would be related to the DC/DC cost model, the heat sink is at the moment oversised and it would be favourable for the cost when a more optimised cooling size, and thus cost, is used.

The topology 1 was selected. This concept incorporates a low-voltage DC-DC converter for every battery module in the system, allowing these units to be placed in series to achieve a controlled DC voltage and in parallel lines to scale total HESS energy capacity (Topology 1).

4.1.4.2 Integrated safe, modular and flexible battery system architecture

Within the deliverable “D3.2 Integrated safe, modular and flexible battery system architecture” [20], the description of the chosen HESS topology is expanded to a detailed HESS architecture. The architecture will be outlined by means of high-level and domain specific requirements.

The architecture has considered TCO (total cost of ownership) and scalability on all domains. Electrical component placement as well as DC-DC converter design has taken production costs into consideration. Scalability of current and energy capacity, cooling and mechanical configuration of the system have been evaluated while establishing the architecture. Special attention was given to the control architecture, which can pose a critical limit to system scalability. This risk was mitigated by using several levels of controllers in the implementation. In the developed architecture, no practical HESS sizing limits exist for the developed control architecture.

For reliability and safety of the HESS architecture, the safety requirements were queried across all domains to ensure they were met across domains.

4.2 CURRENT DIRECT Project

The main source for this section is the publication "A swappable Battery to Reduce Emissions of Ships" [21].

The overall objective of the CURRENT DIRECT project is the development of **a swappable battery energy storage container that operates on an Energy-as-a-Service (EaaS) platform**.

Starting at the component level, CURRENT DIRECT is developing an innovative lithium-ion cell optimised for waterborne transport using novel additive manufacturing techniques to enable consistent cost reduction, increased performance, and flexible production capabilities when compared to conventional techniques. A distributed BMS, referred to as a Single Cell Supervisor (SCS), will be developed to enable granular data management while eliminating the need for wire harness through use of power line communication. A composite material will also be developed that aims to combine thermal and mechanical properties into a single component. The combination of these innovations will be integrated into a pack design to further reduce material and manufacturing costs.

CURRENT DIRECT will optimise the implementation of these innovations with the development of an EaaS platform underpinned by a physics-based battery model to further reduce the barrier for entry and increase market adoption. To support the commercialisation of the EaaS ecosystem (Figure 28) CURRENT DIRECT will define standardised interfaces for the container to support both onshore and vessel operations. Finally, a harmonised battery certification methodology to validate and verify safety will be proposed aiming to reduce time to market to increase competitiveness.

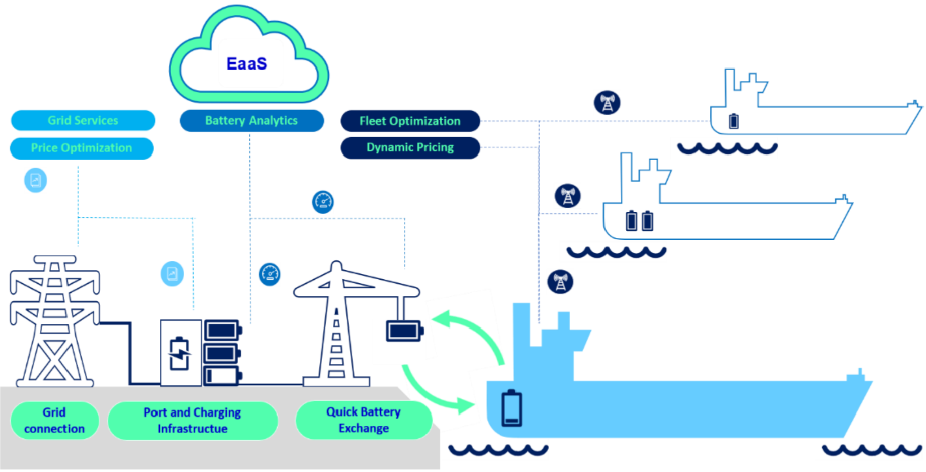


Figure 28 – CURRENT DIRECT ecosystem [22]

One of the main NEMOSHIP objective is to develop and validate a cloud-based digital platform enabling a safe and optimal exploitation of large batteries on-board. It will therefore be particularly interesting and efficient to build on the first results of the SEABAT project to define its requirements. Moreover, NEMOSHIP aims to demonstrate a modular and standardised battery solution integrated within a retrofitted hybrid vessel. The battery energy storage container developed in CURRENT DIRECT could be a reference for this expected outcome.

This section highlights three key points studied in the CURRENT DIRECT project [20]:

- Recommendations for a swappable container design.
- EaaS functionalities and platform.
- Regulatory framework standardisation.

4.2.1 Recommendations for a swappable container design

The space available for installation is often a major restriction towards installing batteries on board vessels. One option is to do the installation in separate deckhouses, fulfilling the requirements set by the class societies. A swappable solution will then enable an easier implementation when compared to fixed installations and will notably support an increase of retrofit installations.

The swappable battery energy storage will be installed in movable 20-foot equivalent standard ISO containers. With the current energy density of battery cells and battery modules, one would typically be able to install 1MWh of energy inside a movable 20-foot equivalent standard ISO container. The batteries inside the containers will be charged at dedicated charging stations on the shore side. The containers will be handled by means of cranes between the shore and the vessel.

A typical battery energy storage installation inside any space, contains in addition to the batteries, a frequency converter converting the batteries DC voltage to AC voltage with a fixed voltage and frequency as well a possible transformer to transform the AC voltage to a suitable voltage level to support the vessels voltage level. As supporting function to this main equipment, HVAC, telematics, control voltage, fire- and gas detection and fire mitigation means are needed.

- AC vs DC

A dedicated white paper [23] provides a summary of the decision-making methodology (Figure 29) to underpin the decision to utilise DC power for the CURRENT DIRECT swappable container battery system. Overall, the DC power option provides the highest number of advantages to the project with only very few disadvantages:

- Maximize energy density in a battery energy storage container.
- Minimum fault occurrence frequency inside the battery energy storage container due to limited number of main components.
- Adaptability to different power levels through the battery energy storage container.
- Bi-directional connectivity to support the connection point on shore side.
- Lower build cost/kWh for the battery energy storage container.

Operational aspects

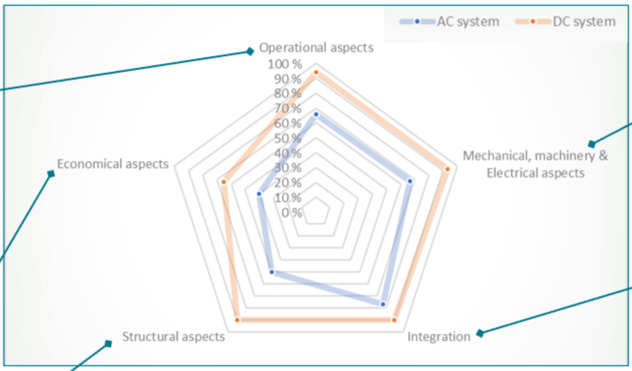
Energy density
Flexibility in design
Adaptability to different power levels
Electrical losses between battery and propulsion unit
Flexibility in main voltage range
Connection and ramp up time
Vessel infrastructure using PTI/PTO

Economical aspects

Cost of building container
Cost of vessel infrastructure
Cost of shore infrastructure
Cost of vessel infrastructure using PTI/PTO

Structural aspects

Complexity of container infrastructure
Fire Safety



Mechanical, machinery & Electrical aspects

Cooling demand
Power connection
Auxiliary systems

Integration of container

Vessel integration, physical
Vessel intergration, electrical
Vessel intergration, control
Onshore integration, electrical
Onshore integration, control
Regulatory

	Operational aspects	Mechanical, machinery & Electrical aspects	Integration	Structural aspects	Economical aspects
AC system	66 %	67 %	77 %	50 %	40 %
DC system	94.3 %	93 %	90 %	90 %	65 %

Figure 29 – Aggregated spider diagram evaluation [21]

- **Container layout and interfaces**

Standardising the design is focused on an ISO container having the appropriate robustness to safely contain a heavy load (the Li-ion battery, ancillaries for electric and thermal protection, HVAC, thermal protection, and firefighting ancillaries, communication equipment) and the geometrical characteristics needed to connect (and disconnect) it to the ship structures and keep the position when the ship is sailing subject to seagoing environmental stresses (Figure 30).

With a fixed installation, the electrical connections to the vessel electrical infrastructure are well defined and easy to implement. Required cooling capacity to remove the generated heat is typically done by connecting the deck house to the vessel cooling circuit and system. The fire protection will be extended from the vessel typical means of fire mitigation. An additional water mist or clean agent is often considered and possibly added as a local mean for reducing the heat extraction in case of thermal runaway incident in the battery space/deck house.

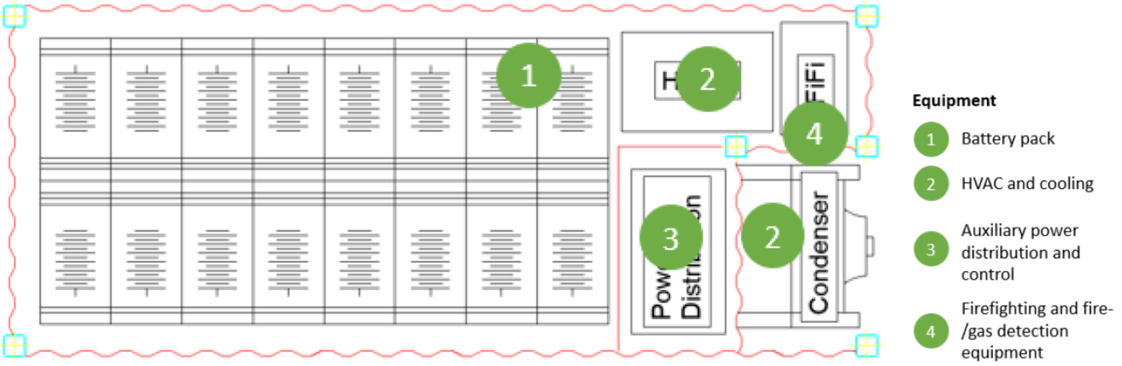


Figure 30 – Layout of a container with DC power solution [23]

The block diagram below (Figure 31) shows the standard mechanical, electrical, and physical interfaces between battery container and vessel. The same interfaces exist between the container and charging station onshore.

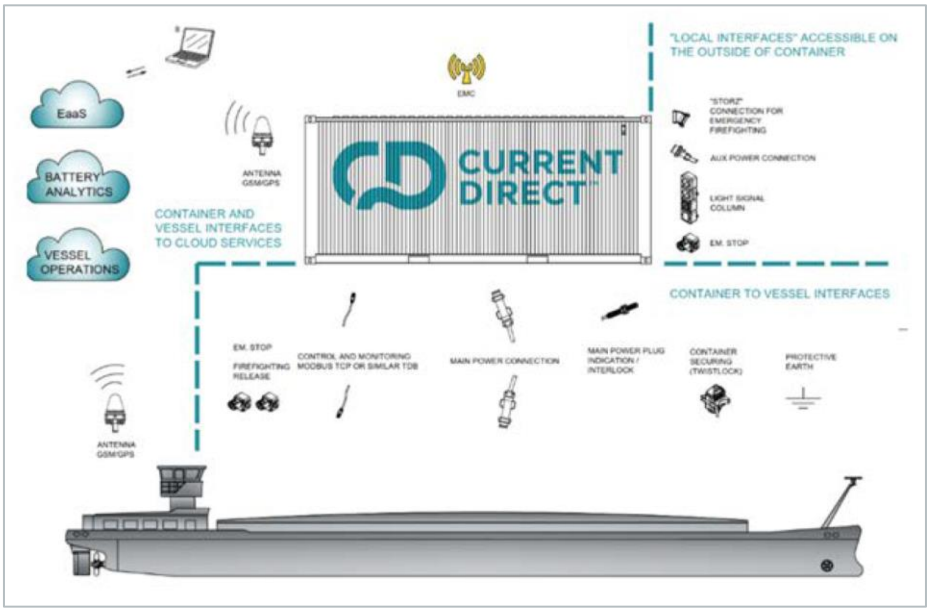


Figure 31 – Interfaces between battery container and vessel [21]

- **Design requirements and KPIs**

The report “D2.1 Design Recommendations Battery” [22] provides in detail the requirements and KPIs for the swappable battery system developed in the CURRENT DIRECT project. The table below (Table 11) lists the main categories considered in this analysis for each sub-system.

Table 11 – Main categories for battery system requirements (CURRENT DIRECT)

Topic	Category
Container	– Physical characteristics (weight, size) – Battery capacity – Safety (Firefighting system, gas detection, exhaust vent, …) – Structure (Fire class & structural integrity) – Electrical system – Electrical & mechanical interfaces – Communication interfaces – HVAC – Service and reliability
Battery pack	– Regulatory certifications – Physical characteristics – Connectors and cables – Performances – Electrical protection and isolation – Safety – Testing – Operating conditions
Composite materials	– Physical characteristics – Performances – Reliability
BMS	– Performances (SOC and SOH estimation, balancing, …) – Operational safety (diagnostics, protection, alert system) – Communication & monitoring (measurements, internet connection, security, system bus) – Smart cell supervisor – Ultrasound sensor

Moreover, the report analyses the recyclability requirements generating a set of design guides for the CURRENT DIRECT battery container. It will include the impacts of all non-cell material selections, disassembly techniques, and the scale of minimum disassembly units permissible for planned recycling processes. A key focus of the task will be designing for safe disassembly, recycling, and disposal of the CURRENT DIRECT battery containers at their end of life. This will be an input to the design reviews to ensure that at end-of-life future cost of recycling and non-reusable waste is minimised.

4.2.2 Energy as a Service (EaaS) functionalities and platform

Energy-as-a-Service is a business model, which directly relates the cost of the battery to its usage. The goal is 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. Such a complex structure requires the deployment of a monitoring system that processes information, decides, and provides directions. As a consequence, a cloud based EaaS platform is being developed. This type of platform comprises of the built-in control unit and the web platform:

- The control unit is responsible for the optimisation of the entire logistic process. It aims to tackle the optimal energy transfer of the batteries (when to recharge/reserve batteries), manage the battery fleet between the electric vessels and the EaaS stations, and incorporate recognised practises of revenue management (pricing optimisation and service fee calculation). All the above are developed to ensure that the end-users have the energy needed, when they need it, at a competitive price, comparable to today’s fossil fuels. EaaS platform is the system under which connects all the functionalities needed for the continuous operation of the battery swapping network.
- The web platform is the environment which allows the users to review information on demand and to interact with the functional components of the EaaS platform (Figure 32). Each user, depending on its type, will have different privileges and access to different data and operations of the platform.

In [21], the core functionalities of the EaaS platform are presented:

- Infrastructure planning to support the deployment of the infrastructure of the EaaS network mainly in terms of number and optimal locations of shore stations.
- Fleet management / route planning to support end-users in minimising the cost (the service fee for the use of the EaaS network) while guaranteeing continuity of the services.
- Charging scheduling to maintain high quality of service (QoS) while minimising the charging cost (ea. maximising the efficiency of the system).

Figure 32 – Overview of the CURRENT DIRECT EaaS network [24]

The report “D2.2 Design Recommendations EaaS” [24] provides in detail the requirements and KPIs for the EaaS platform developed in the CURRENT DIRECT project. The table below (Table 12) lists the main categories consider in this analysis for each sub-system.

Table 12 – Main categories for EaaS platform development (CURRENT DIRECT)

Topic	Category
EaaS database	- Security (encrypted data exchange) - Data (battery and auxiliary) - Reliability and scalability
EaaS battery analytics	- Data format, live graphs - Data security - API
Physics based SOH model	- Model structure - Lifetime energy estimation - Cloud-based computation
EaaS container fleet optimisation	- Location tracking - Safety (access, SSL encryption, data protection) - Cloud-based software
EaaS payment platform	- Regulatory - Safety
User interfaces	- Safety (access, protection encryption) - Data format and accessibility - Local & cloud software

4.2.3 Regulatory framework standardisation

The innovative solution of having the source of power for a ship contained in a container that could be replaced with easy and quick operation, leads to the need to standardise the container itself and its interface facilities. An industry-agreed regulatory framework would allow different manufacturers to supply standardized swappable containerised battery to the market.

The Li-ion battery are largely regulated by international standards, classification societies and some flag administrations issued additional prescriptions for the safe use of such equipment [26]. There are industry initiatives [27] within the maritime community having as an objective the standardisation of the lithium battery requirements.

On a side of the design requirements, there shall be a set of standardised testing procedures and acceptance criteria, to complete the assurance process of the whole containerised battery system and a process ensuring that the characteristics of the system remain within acceptable limits until the end of life. Such a process is well consolidated for the ship structures, machinery and safety equipment permanently installed onboard and is based on continuous surveys carried out by the classification societies and the flag administrations but is missing for equipment that are removable and replaceable (swappable) from the ships and provide essential services for the ship.

The certification process will be based on a combination of selected requirements from existing regulatory frameworks and the outcomes from an appropriate risk management process:

- Existing requirements for structures, electric equipment, lithium battery and fire safety systems have been collected from the existing applicable regulatory framework. The ship rules from Lloyd’s Register, DNV-GL and ABS have been considered as the basement together with the International Electrotechnical Commission Standards (IEC62619 and IEC62620).
- The Lloyd’s Register risk based certification [28] process is identified as the tool to implement the activities of risk management by risks identification and mitigation. The areas of risks include the cyber security [29] with particular focus to the EaaS and the whole container monitoring, control, and safety systems.

5 Lesson learnt summary

The below section summarises lessons learnt from both a technical and non-technical perspective.

5.1 Technical perspective

Figure 33 summarises the technical conclusions and lessons learnt. In the following sections general conclusions, and collection of specific conclusions are presented regarding each identified section.

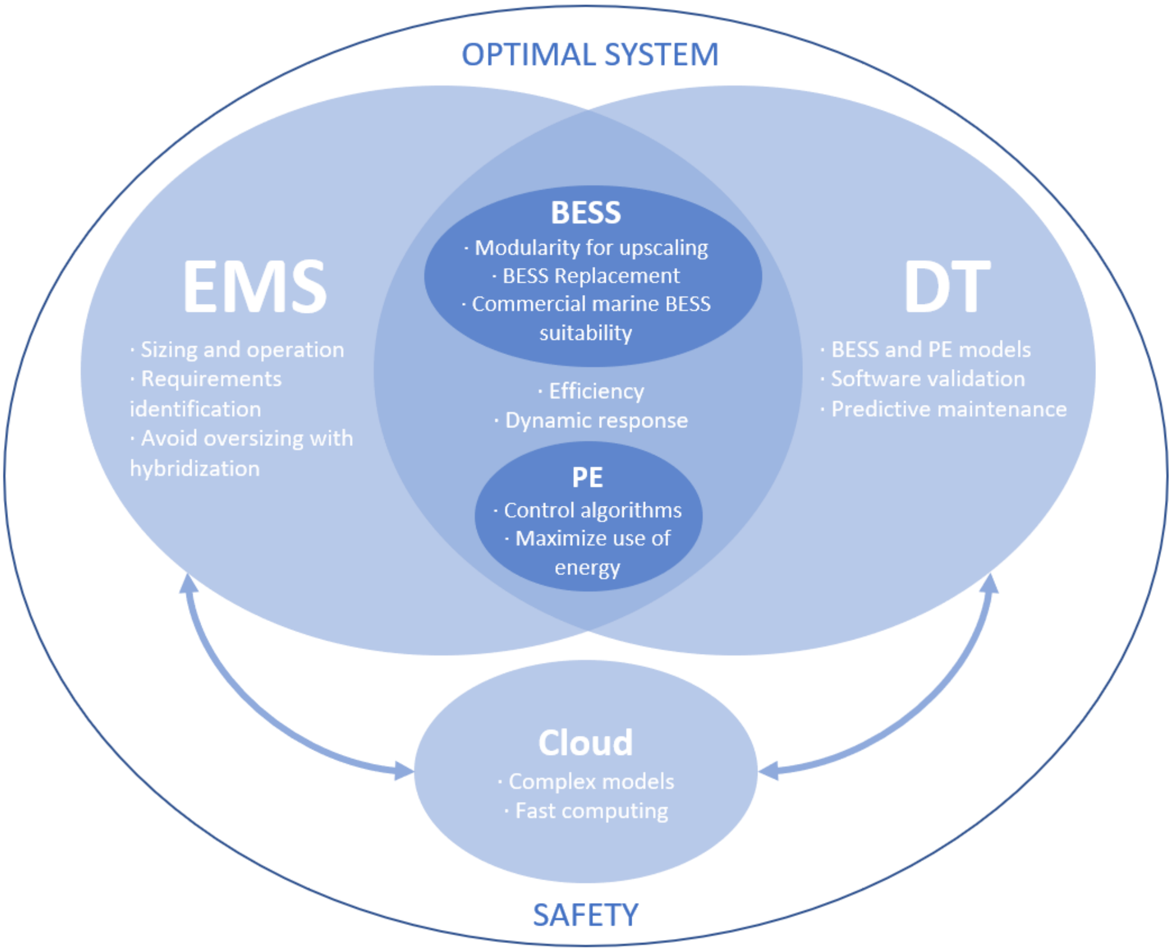


Figure 33 – Summary of conclusions and lessons learnt

5.1.1 EMS (sizing and operation)

Regarding the EMS, it is important to consider both design and operation processes. For both, it is necessary to identify the requirements of the system and the operation profile. Then, optimal ESS can be defined, as well as energy source for each operation phase.

ESS can be hybridised to avoid oversising. This can be done with different battery chemistries, (such as LTO and NMC) or different ESS technologies, such as fuel and batteries. Anyway, it is important to evaluate if hybridisation is worthwhile for the application.

For the optimal performance, prediction and BESS models should be improved for more accurate behaviour estimation and control.

Based on the analysis carried out in this report, a selection of lessons learnt regarding EMS is provided below:

- Control algorithms need to be developed in such innovative systems. EMS is relevant to guarantee power supply as well as optimising fuel consumption and asset lifetime. (NAUTILUS)
- Ship operators must lead with loading scenario which reconciles several operational, economic and maritime criteria while permitting the reduction of fuel consumption. (JOULES)
- The speed is a major influencer of engine power rating, if reduced it can consequently reduce power need. (MARANDA)
- Priorities of optimisation can vary depending on the phase of the travel. So, travel phases identification may be helpful also. (FUTPRINT50)
- Regarding the EMS, it is important to consider both the generation system architecture and the performance requirement in each travelling phase. This way, available energy can be optimised from both the design and operational perspectives. (FUTPRINT50)
- A very large number of vessels are overpowered. Therefore, asking vessel owners to describe their current solution is unfavourable to fuel cells, which would benefit from being dimensioned to fit the need. As the power need cannot be reasonably derived from speed and other parameters (unless entering into detailed calculation per vessel category, costly to develop) it was decided to use power need as a primary input. (MARANDA)
- Fuel production environmental impact should always be considered in the decision-making process. This is mainly due to the fact that, by using sustainable fuels from renewable energies, environmental impacts potentially are shifting from operation phase to energy production phase. (JOULES)

5.1.2 Optimisation

Technological improvements must go along with optimal operations. This means that optimisation techniques must be effective to achieve an optimal combination of reducing fuel consumption, CO_2 emission, and project costs on the one hand, while increasing the efficiency of the system, its lifetime, and even the volumetric energy density (more energy in less space) on the other hand. For the overall system to be optimal, it will also be necessary to meet the system requirements and maximise the utilisation of available resources.

Based on the analysis carried out in this report, a selection of lessons learnt regarding optimisation is provided below:

- Energy grid optimisation could improve the environmental performance by up to 20 %. Developing and building these innovative ships will cost a lot of time and money and there will still be risks that technologies might not be in place as required. (JOULES)
- The power sharing between high-power and high-energy storage systems is optimised to control and shift the high-frequency and high-slope currents from the lithium-ion battery pack to lithium-ion capacitor in terms of life-time 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)

5.1.3 Cloud programming

For the system to be optimal, it is important also that the computational system is optimal. This can be achieved with cloud computing since more resources are available and computational time is reduced. At the same time, more complex and accurate models can be built and managed.

Based on the analysis carried out in this report, a selection of lessons learnt regarding cloud programming is provided below:

- Significant industrial barriers need to be overcome to develop technological innovations. For instance, the minoritary development of cross-sectoral tools or the reduced efforts on greening our ocean economies. (COLUMBUS)
- Process communication interfaces will define the operation of the system, so they must be properly selected. (HYBRIS)
- Implemented in a server in the cloud, the advanced BMS solution will benefit from more computational resources with the possibility to further develop complex storage system models. (HYBRIS)

5.1.4 BESS marine market

Nowadays, ESS technologies for marine applications available in the market are not optimal for operational requirements of the ships. These require high energy systems but also high c-rates sometimes. The nature of current battery technologies used in vessels leads to oversizing the battery in order to be able to withstand those high c-rates. In this case, hybridisation can be a solution depending on the operation profiles.

Based on the analysis carried out in this report, a selection of lessons learnt regarding BESS marine market is provided below:

- FP cells are selected for the HE battery pack, and NMC cells are considered for the HP battery pack, based on the consortium estimations and information available with regard to cost and cyclability. In particular, 2nd-life batteries are not a viable option at the time of reporting (Nov 2021) due to relatively high cost and limited market maturity, but they may become a very interesting option. (ISTORMY)
- The major challenges of hybrid electric aircrafts are in the energy density of batteries, the thermal management of power train, the overall modelling of the subsystems and their interactions, and the identification of certification requirements. (FUTPRINT50)

5.1.5 Hybridisation

Based on the analysis carried out in this report, a selection of lessons learnt regarding hybridization is provided below:

- The SOFC-BAT system is interfaced with tailored power electronics. In this regard, it has been defined that separate DC/DC converters for SOFC and BAT systems need to be placed in different rooms due to the significant differences in operational conditions (mainly operation temperatures and DC voltage values). Differences in operation conditions of the hybridised technologies need to be considered for power electronics selection and location. (NAUTILUS)
- Hybridisation gives the ability to cover all necessary requirements, avoiding oversise. (MARANDA)
- 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. (JOULES)
- Important and challenging to find optimum combination of choice of sustainable fuel and onboard ship technologies to reach cost effective GHG reductions. (JOULES)
- The HESS combines the high energy efficiency and fast response of the LTO, whose storage capacity is expanded thanks to the AORFB; this results in a final system capable of covering a large part of the needs that an energy storage system may have, saving investment and gaining performance. (HYBRIS)
- First optimum selection of components is necessary (regardless of whether it is a hybrid or non-hybrid system), with a later maximising or optimising resources/energy during operation. (FUTPRINT50)

5.1.6 Design

Based on the analysis carried out in this report, a selection of lessons learnt regarding design is provided below:

- JOULES project's ship design methodology combines energy grid simulations of the entire ship with an integrated LCPA (holistic economic and ecological assessment methodology of fuel production). (JOULES)
- Due to the huge amount of individual components, a detailed LCA is far too much work and impossible to carry out at the early design stage. (JOULES)
- At the beginning of the project, it is important to identify constraints related to operating conditions, installation requirements and safety issues. (HYBRIS)
- The lack of input data can affect the results obtained, such as lack of consumption behaviour and generation capacity data to estimate energy cost. (HYBRIS)
- The system should be effective and offer service flexibility from the user point of view. (HYBRIS)
- KPIs for the selection of most attractive ship design: net present value, cumulated energy demand, global warming potential, acidification potential, eutrophication potential and aerosol formation potential (some of them may be difficult to calculate). (JOULES)
- Developing and building these innovative ships will cost a lot of time and money and there will still be risks that technologies might not be in place as required. (JOULES)

5.1.7 Upscaling

According to one of the projects, in a real system of 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.

Based on the analysis carried out in this report, a selection of lessons learnt regarding upscaling and construction is provided below:

- Modularity is a key feature when trying to scale functional prototypes to multi-MW systems. (E-FERRY)
- It is necessary to assign more clear roles and responsibilities in such a complicated project that includes construction of major components. (E-FERRY)
- The vessel automation and the power management system are combined into one system in the vessel, which is reducing the number of the external connections. (MARANDA)
- The HESS is containerised to make easier the transportation, considering the prototype dimensions. (HYBRIS)

5.1.8 Dynamic response

The system from both a technical and algorithm point of view should consider dynamic responses and manage the necessary energy for those situations.

Based on the analysis carried out in this report, a selection of lessons learnt regarding dynamic response is provided below:

- The SOFC technology has some limitations in terms of dynamic response. Hence the battery system will be in charge of supplying the load fluctuations. (NAUTILUS)

5.1.9 Power electronics

The ESS system includes the necessary power electronics for the integration of both BMS and EMS. 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 PE is also modelled, since it is where the control algorithm is implemented. Therefore, complex models are necessary, even more if technologies are hybridised.

Based on the analysis carried out in this report, a selection of lessons learnt regarding PE is provided below:

- For the testing of the real prototype, it must be considered as an integrated system, including BESS and PCS. It will include HESS model, virtual demonstration site test, grid emulation model and historical data. This way the integration of the model into the electric system will be possible. (HYBRIS)
- Technology development through the increment of efficiency leads to the integration of new electric/electronic equipment. This results in an increment in the supply power required, and thus the need for heat dissipation also increases. Additionally, electronics tends to be smaller and

smaller, so the heat in each area is more concentrated. Consequently, TMS is key for the proper operation of the system. (FUTPRINT50)

5.1.10 Safety measures

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.

Based on the analysis carried out in this report, a selection of lessons learnt regarding security is provided below:

- There may be a dependence on software for decision making due to the complexity and urgency of problems/accidents. This means that they have to be autonomous and really accurate. (JOULES)

5.1.11 Charging stations

In the projects reviewed, it is also mentioned that for fast charging, sophisticated infrastructures should be implemented, but in the NEMOSHIP project the charging station will not be considered. Only frequent or optimal charging strategies will be considered in order to extend the ranges of routes.

Based on the analysis carried out in this report, a selection of lessons learnt regarding charging stations is provided below:

- The electrical infrastructure and charging system should be constructed on different owner-terms, which would lead to both lower investment costs and lower costs per-kWh for the charged electricity. (E-FERRY)

5.1.12 Heat recovery system

Heat recovery systems could also be interesting, but it is another aspect which is not addressed in NEMOSHIP. In case of vessels, it could be useful for the battery thermal management since it can highly impact the performance.

Based on the analysis carried out in this report, a selection of lessons learnt regarding heat recovery systems is provided below:

- As previous steps to full electrification or e-fuel adoption, primary energy converter efficiency augmentation and energy recovery system implementation have been seen as strong alternatives. (JOULES)

5.2 Non-technical perspective

5.2.1 Information availability

Based on the analysis carried out in this report, a selection of lessons learnt regarding information availability is provided below:

- Information does not reach the right people thereby new communication campaigns might be needed. (LASTING)

- EU RD&I projects websites should be better structured and provide more information. Besides, it would be interesting that these websites remained online for a longer period after the project end. (LASTING)
- There is information available on technical aspects, but less on the economics and business models related to technical innovations. Moreover, there is limited information on the uptake of such innovations that come from EU RD&I projects. Organisations have a great need for information in the uptake phase, in which innovations are applied in a real business environment. (LASTING)
- Companies, particularly SMEs, may not be fully aware how business models are going to change due to climate and circular economy targets. (LASTING)
- Much of the critical information from RD&I projects is not made public, which makes it impossible to follow up on the detailed results.
- It is necessary to work on easy to read and understand information sources, especially for SMEs, which may be less informed about project opportunities and EU RD&I project results. Organisations like industry associations and other non-profit organisations should play a stronger role in this regard. (LASTING)
- Reported information from EU RD&I should be better structured on the website, as well as better filtered so as to ease users value extraction. Information accessibility has also been identified as a bottleneck in this regard. (LASTING)
- Some of the abovementioned gaps could be covered by industry associations and other non-profit organisations. (LASTING)
- Science-policy communication needs to be improved, particularly when it comes to coordination of different sectors and actors in the maritime sectors. (COLUMBUS)
- It is necessary to foster the cooperation and communication with policy and scientific actors using platforms like WATERBORNE or EU collaboration projects. (COLUMBUS)
- The lack of free and open-access multi-purpose data repositories and portals. (COLUMBUS)
- Project partners developed a step-wise, “COLUMBUS Knowledge Transfer Methodology” based on the identification and collection of knowledge outputs. (COLUMBUS)
- Both internal and external activities help to encourage the exchange of knowledge within the consortium and potential stakeholders, professionals, researchers, students, and the general public. (HYBRIS)
- Communication materials are important to keep all project stakeholders and interested parties informed. They should be updated as the project develops. In this way, fundamental knowledge and deeper understanding is ensured, which encourages greater engagement and active participation. (HYBRIS)

5.2.2 Professional skills

One challenge or gap identified related to ESS integration in vessels is the lack of professional skills in different aspects. On the one hand, there is not a specific professional profile for the building of tailor-made vessels which integrates ESS. On the other hand, the vessels crews themselves are not prepared to manage the operation of an ESS, as they have limited training in this area. There is also lack of core manufacturers of ESS in vessels. It could also help to assign more clear roles and responsibilities that includes construction of major components.

Based on the analysis carried out in this report, a selection of lessons learnt regarding professional skills is provided below:

- The lack of skilled workforce shows a clear existing skill gap. (COLUMBUS)
- Other important savings were achieved via crew cost, as the E-FERRY is approved to sail without a marine engineer. Instead, a service engineer takes care of maintenance (that is less demanding). (E-FERRY)

5.2.3 Regulatory framework

The future of technical solutions and the creation of jobs and services in our society may be limited by the lack of an adequate regulatory framework. It is therefore important to contribute to the development of such regulatory framework.

Based on the analysis carried out in this report, a selection of lessons learnt regarding regulations and standards is provided below:

- The impact has been maximised through liaison with a project advisory board consisting of industry stakeholders and also in liaison with Regulations, Codes and Standards (RCS) drafting organisations. the advisory board would e.g. provide inputs on business case scenarios (MARANDA)
- The uncomplete establishing/adoption of the appropriate legal framework. (COLUMBUS)
- In order to follow up standardisation, it could be interesting to join international technical committees (TCs) to be updated. Dissemination material could be delivered to TCs and even develop new standard(s)s or reference(s). (HYBRIS)

5.2.4 Technology development

It will cost time and money to develop and build these innovative vessels, and there will continue to be risks that the technologies might not be in place as required. (JOULES)

5.2.5 Stakeholders interaction

Based on the analysis carried out in this report, a selection of lessons learnt regarding stakeholders relation and risks is provided below:

- The end user groups strongly agreed (66%) that there is not enough engagement with stakeholders/end users, rating this to be the top barrier for efficient knowledge transfer. (COLUMBUS)
- The project has a YouTube, LinkedIn, twitter, and Instagram accounts, as well as a Research Gate and Zenodo profiles. (FUTPRINT50)
- Finding specific equipment suppliers, mainly when it comes to innovative technologies can be challenging. (JOULES)

6 References

[1] E-FERRY Project, «D7.5 Final validation and evaluation report,» 2020.

[2] A. Ansar, «NAUTILUS Workshop,» 2022. [En ligne]. Available: https://nautilus-project.eu/media-download/presentations.

[3] NAUTILUS Project. [En ligne]. Available: https://nautilus-project.eu/news/the-energy-management-unit-of-the-hybrid-propulsion-system-genset.

[4] MARANDA Project, «D2.1 Specification report,» 2017.

[5] MARANDA Project, «D7.1 Design and layout of fuel cell system into 10ft container for durability testing in Äetsä,» 2017.

[6] MARANDA Project, «D9.3 Report on business analysis tool design and use,» 2017.

[7] COLUMBUS Project, «D.2.2 Guidelines on carrying out COLUMBUS knowledge transfer and impact measurement,» 2015.

[8] ORCA Project, «D3.5 Report on the rechargeable energy storage system,» 2022.

[9] ORCA Project, «D2.2. Report on virtual simulation tool verifications,» 2021.

[10] HYBRIS Project. [En ligne]. Available: https://hybris-project.eu/technology/abms/.

[11] iSTORMY Project. [En ligne]. Available: https://istormy.eu/project-introduction/.

[12] iSTORMY Project, «D3.2 Report on the high-fidelity modelling of the PE interface incl. Digital Twin,» 2021.

[13] iSTORMY Project, «D3.1 Report on the design optimisation framework of the power electronics interfaces,» 2021.

[14] A. Spinelli, «Application of probabilistic principles to set-based design for the optimisation of a hybrid-electric propulsion system,» *IOP Conference Series: Materials Science and Engineering,* 2022.

[15] SEABAT Project. [En ligne]. Available: https://seabat-h2020.eu/.

[16] SEABAT Project, «D2.1 Application matrix,» 2021.

[17] SEABAT Project, «D2.2 Key performance indicators list,» 2021.

[18] SEABAT Project, «D2.3 Detailed requirements document,» 2021.

[19] SEABAT Project, «D3.1 Evaluation and selection of architectural concepts,» 2021.

[20] SEABAT Project, «D3.2 Integrated safe, modular and flexible battery system architecture,» 2022.

[21] P. Scialla, M. Roiaz, R. Kostos, S. White, D. Kontosfyris et J.-E. Räsänen, «A swappable battery to reduce emissions of ships,» *Progress in Marine Science and Technology,* vol. Technology and Science for the Ships of the Future, 2022.

[22] CURRENT DIRECT Project, «D2.1 Design recommendations battery,» 2021.

[23] CURRENT DIRECT Project, «Container battery energy storage system AC vs DC decision white paper,» 2021.

[24] CURRENT DIRECT Project. [En ligne]. Available: https://www.currentdirect.eu/the-project/.

[25] CURRENT DIRECT Project, «D2.2 Design recommandations EaaS,» 2021.

[26] Norwegian Maritime Authority, «Circular RSV12-2016 Guidelines for chemical energy storage,» 2016.

[27] Maritime Battery Forum. [En ligne]. Available: https://www.maritimebatteryforum.com/.

[28] Lloyd's Register, «ShipRight design and construction - Risk management - Risk based certification,» 2021.

[29] Lloyd's Register, «ShipRight linked supporting services - Procedures for the assessment of cyber security for ships and ships systems,» 2021.

Appendix A - Glossary

Table 13 – List of abbreviations used in the document

Abbreviation	
ABMS	Advanced BMS
ADOPT	Augmented Design and Optimisation
AI	Artificial Intelligence
ALT	Alternative Energy for Transport
ANSI	American National Standards Institute
AORFB	Aqueous Organic Redox Flow batteries
BAT	Battery System
BESS	Battery ESS
BMS	Battery Management System
BMU	Battery Management Unit
CAT	Connected and Automated Transport
CFR	Carbon Fibre Reinforced
CRM	Common Research Model
CSA	Coordination and Support Action
COP21	21st Conference of the Parties, or Paris Climate Conference
C&I	Commercial and Industrial
DLL	Dynamic Link Library
DNA	Deoxyribonucleic Acid
DoD	Depth of Discharge
DS	Digital Shadow
DT	Digital Twin
DTH	DT for HESS
EaaS	Energy as a Service
EASN	European Aeronautics Science Network
ECU	Engine Control Unit
EIS	Entry into service
ELT	Transport Electrification
ESS	Energy Storage System
EMS	Energy Management System
EV	Electric Vehicle
FCH	Fuel Cell and Hydrogen joint undertaking
FCPM	Fuel Cell Power Module
FCR	Frequency Regulation
FTP Code	Fire Test Procedures Code
GHG	Greenhouse Gas
HE	High Energy

HEA	Hybrid Electric Aircraft
HESS	Hybrid Energy Storage System
HEU	Horizon Europe
HIL	Hardware In the Loop
HLCS	High-Level Control System
HP	High Power
HW	Hardware
H2020	Horizon 2020
IAS	Integrated Automation System
IACS	Industrial Automation and Control System
ICE	Internal Combustion Engine
IMO	International Maritime Organization
INF	Transport Infrastructure
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
LCPA	Life Cycle Performance Assessment
LFP	Lithium Ferro-Phosphate
Li-Ion	Lithium-Ion
LTO	Lithium-Titanium-Oxide
NMC	Nickel Manganese Cobalt
NT	Non-Technical
NTM	Network and Traffic Management systems
ME	Medium Energy
OEI	One Engine Inoperative
PCS	Power Conversion System
PE	Power Electronics
PEMFC	Proton-Exchange Membrane Fuel Cell
PHEV	Plug-in Hybrid EV
PMS	Power Management System
RCS	Regulations, Codes and Standards
RD&I	Research, Development and Innovation
RES	Renewable Energy Sources
RIA	Research and Innovation Actions
R&D	Research and Development
SBD	Set-Based Design
SCS	Single Cell Supervisor
SH-EMS	Self-Healing EMS
SME	Small and/or Medium Enterprises
SMO	Smart Mobility and Services
SOC	State of Charge

SOFC	Solid Oxide Fuel Cell
SOH	State of Health
STRIA	Strategic Transport Research and Innovation Agenda
T	Technical
TCO	Total Cost of Ownership
TCP/IP	Transmission Control Protocol/Internet Protocol
TCs	Technical Committees
THCC	Typhoon HIL Control Center
TLAR	Top-Level Aircraft Requirements
TMS	Thermal Management System
TRIMIS	Transport Research and Innovation Monitoring and Information System
TRL	Technology Readiness Level
VDM	Vehicle Design and Manufacturing
VGS	Virtual Genset Simulator
ZEWT	Zero Emission Waterborne Transport

Appendix B - Regional projects

One of the aims of the present report was to analyse projects previously funded under the H2020 and HEU programmes. Nevertheless, some regional projects are worth mentioning too – this appendix provides further details about these.

1. Battery Digital Twins

Date: 01/11/2022 - 29/04/2023
Country: United Kingdom
Sector: General-multisector

A **battery twin** was implemented in micromobility devices. An **AI-based predictive maintenance** was developed, the main goal of which is to extend battery lifetime by continuously tracking battery key health parameters and by optimising dynamically battery usage. The digital twin fuses state-of-the-art battery models with real-time data measurements and machine learning algorithms.

2. Hybrid Battery Optimisation

Date: 30/06/2019 - 30/08/2021
Country: United Kingdom
Sector: E-mobility

After a simulation process, the selected **HESS** was designed and built. Moreover, a novel **BMS** was developed.

3. An Advanced Battery Energy Storage Control System for Predictive Maintenance

Date: 01/02/2020 - 30/10/2021
Country: United Kingdom
Sector: Stationary

Regarding ESS integration, a low-cost and easy to maintain li-ion battery system was designed and tested. Unconventional architecture and innovative electronics and sensors were used, which allow these batteries **to be reused** to support distributed generation. Moreover, an advanced system to collect and analyse the data for **predictive maintenance** was developed.

4. The Conversion of the UK's First Domestic Passenger Vessel to Fully Electric Propulsion

Date: 30/09/2020 - 30/03/2022
Country: United Kingdom
Sector: Waterborne transport

A diesel vessel was converted to **full electric (battery) and innovative control** systems are also developed. Other aspects like crew and passenger **training** or social engagement were also covered.

5. Zero Emission Systems for Ship Propulsion

Date: 31/03/2021 - 31/01/2023
Country: United Kingdom
Sector: Waterborne transport

High-efficiency, low- or zero-emission ship propulsion systems was developed. Through the design, development and **integration of battery systems**, commercially viable options are offered that reduce ship pollution, provide operational benefits, and reduce environmental impact.

6. Hybridisation of Fishing Vessel Propulsion

Date: 01/01/2020 – X
Country: The Netherlands
Sector: Waterborne transport

In this project, the feasibility to **hybridise** the powertrain of existing fishing vessels and change it to a **diesel electrical** system is investigated.

7. Green Sailing

Date: 01/01/2017 – X
Country: The Netherlands
Sector: Waterborne transport

A sustainable solution for the maritime sector E-naval develops a **hybrid** drive system based on **batteries and hydrogen**.

8. Low Energy Battery Management System for the Maritime Sector

Date: 01/01/2018 – X
Country: The Netherlands
Sector: Waterborne transport

The intention of this project is to develop a **BMS** that improves control **over individual battery cells**. The BMS does this by consuming much less energy itself and physically switching off cells when voltage threatens to become too low.

9. INTENS HyPro

Date: 02/11/2017 - 30/11/2020
Country: The Netherlands
Sector: Waterborne transport

In this project, a **hybrid** power vessel is designed, and component sizing is optimised for **peak power shaving** application. Moreover, it focuses on onboard **multipurpose batteries** and its applications, as well as the conception of a distributed power system.

10. Electrical Solutions for Enabling Zero Emission Ferries

Date: 01/01/2017 - 31/12/2018
Country: Norway
Sector: Waterborne transport

Designated **BMS** algorithms were developed to control equal load in all batteries. Regarding the batteries, this project concludes that in order to keep de operation up and running, a zero-emission ferry must have **at least two drive trains and two battery packs** in case of a fault.

11. New Energy Storage System

Date: 01/01/2017 - 31/12/2022
Country: Norway
Sector: General-multisector

An energy storage system is developed that includes advanced **electrochemical batteries** and other **hybrid technologies** which energy density and power cycling capabilities will increase over time. This project also developed **new control algorithms** and topologies for different combinations of energy storage technologies.

12. DTYard - Digital Twin Yard

Date: 01/01/2019 - 31/12/2022
Country: Norway
Sector: Waterborne transport

This project focused on enabling **collaborative system simulations** for the maritime industry, and help solving the increasing challenges in designing, building, integrating, commissioning, operating and assuring complex, integrated systems and software.

13. ZeFF - Zero Emission Fast Ferry

Date: 01/01/2018 - 31/12/2021
Country: Norway
Sector: Waterborne transport

This project develops a solution for a marine zero-emission energy system than integrates available **battery technologies and PEM fuel cell** technology.

14. Optimising Marine Battery Operations Using 6 Years Operational Data from Commercially Operating Vessels

Date: 01/01/2021 - 31/12/2026
Country: Norway
Sector: Waterborne transport

In this project a novel Marine Battery (MB) **optimal operational models** are developed analysing 6-year operation data. It will integrate three MB operational modules: 1) **data analysis** and learning module to highlight MB performances where most improvements could be gained, 2) MB **degradation diagnosis** and laboratory testing, and 3) MB operations with the **existing**

onshore and future offshore charging facilities. Then new MB optimal models are comprehensively **tested** by two commercial vessels for 2.5 years. In the first year of testing significantlearnings have been identified.

15. OptHyMob - Optimised Hydrogen Powered Maritime Mobility

Date: 2022 – 2025
Country: Norway
Sector: Waterborne transport

This project analyses experimental and full-scale operational data to understand how **fuel cells and batteries** affect each other and how they can best be used together to minimise degradation and **extend lifetime**. Besides, this project uses this information to develop **power balance optimising systems** for a vessel consisting of several batteries and fuel cells.

16. ZELAG

Date: 03/2017 - 05/2018
Country: Italy
Sector: Waterborne transport

The ZELAG project proposes an **eco-sustainable solution** for public transport in inland waters: a boat is built and equipped with **hybrid-electric** propulsion, which allowed the total reduction of polluting emissions and radiated noise.

17. Port Liner

Date: 2017 – X
Country: The Netherlands
Sector: Waterborne transport

In this project, six inland waterway vessels for container transport, with **full electrical** propulsion, fed by batteries (1.6 MW) containerised in E-Powerboxes are **built and put into operation**. The project includes preparatory tasks, final design, engineering, and construction of E-Powerboxes and installation in the newly built inland vessels. The E-Powerboxes will power the propulsion system of the vessels and will be **swapped at port** terminals for charging.

18. LESS

Date: 04/2017 - 06/2018
Country: Italy
Sector: Waterborne transport

This project develops a **software simulation environment** to evaluate the energy performance of different ship types, primarily cruise ships, considering a variety of plant configurations. In particular, it allows the evaluation of alternative plant configurations for heat recovery considering a variety of **operating conditions** representative of one or more operating profiles, in order to also **evaluate and optimise energy efficiency** through cogeneration and appropriate recovery plants.

19. INSYDE-PRO-SHIPS - Study of Insulating Systems Design and Verification Processed for Shipboard Integrated Power Systems

Date: 10/2018 - 12/2019
Country: Italy
Sector: Waterborne transport

The aim of this project is to improve the design and **verification processes of electrical insulating** systems on electric propulsion ships. The project made possible an increase in the reliability of the electrical system on board, in order not only to comply with the regulations on the **safety** of passengers on board ships (safe return to port legislation), but also to **limit the costs due to repair/replacement** activities.

20. PIEZO - Plug-In Electric Zero-Emission Offshore-ship

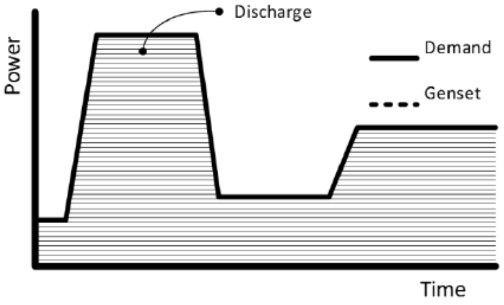
Date: 2020-2023
Country: Norway
Sector: Waterborne transport

This project develops a **plug-in electric Platform Supply Vessel (PSV)** design using primarily batteries, for use on short-medium range routes. It finds solutions to the technical and logistical challenges of **recharging ships offshore**. Big data methods are applied to improve overall energy efficiency throughout the ship. Smarter energy management systems are also developed in this project.

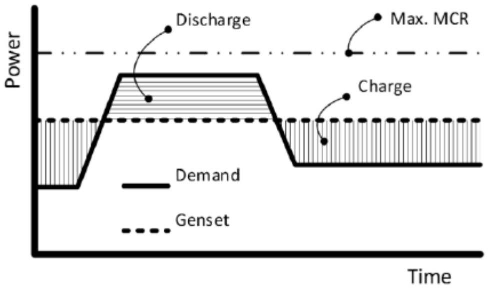
Appendix C - Marine batteries applications

Seven different applications of marine batteries are identified in the SEABAT deliverables.

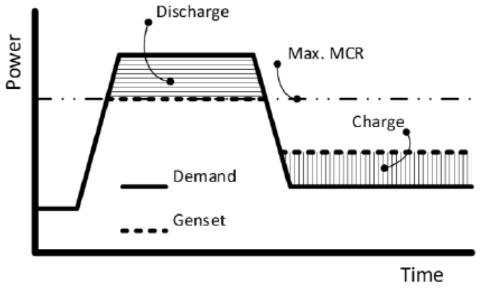
Full electric: the batteries supply the total load demand coming from the propulsion system as well as auxiliary systems on board. This is the type of application, which is used for fully battery powered vessels, but it can also be part of the operational profile of a hybrid vessel, if a fully electric mode is defined.



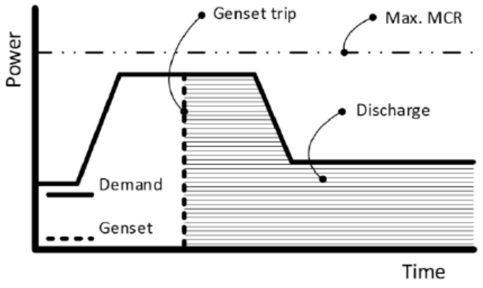
Load levelling: Load levelling is an application used to keep the load on the Diesel engine or generator stable at one efficient level and to reduce the required maintenance, which can be increased by large load fluctuations.



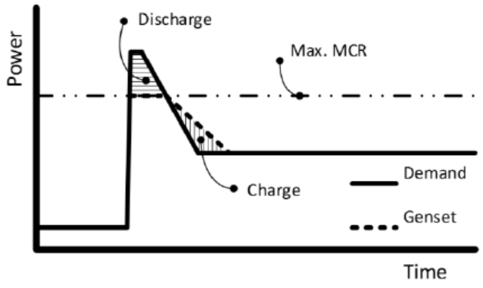
Boost function: The boost function is an application where the batteries are used to increase (boost) the performance of a propulsion system by providing additional power to cover the peaks in demand. The batteries are charged when the demand is below a certain level again.



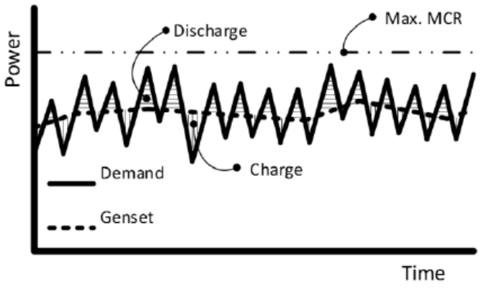
Spinning reserve: Vessels which require an additional level of power redundancy, constant or during specific types of operations, such as dynamic position, currently provide this redundancy by having more generators running than actually required. This redundancy can be achieved by adding a battery to the system, which can supply the load instantaneously when needed, without wasting energy when it is not needed.



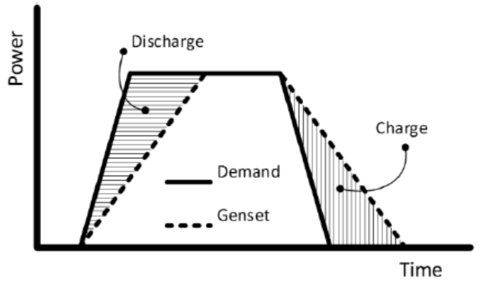
Peak shaving: The peak shaving application uses the battery to take care of sudden peaks and fluctuations in power demand. This reduces the peaks in load demand on the diesel engine or generator, reducing the required maintenance. It can also be used as a bridging function between starting up of an additional generator.



Load smoothing: The load smoothing application is comparable to the load levelling application. The battery system is used to keep the load on a diesel engine or generator at a stable level. The difference between load levelling and load smoothing is the frequency at which the loads fluctuate. Load smoothing is usually considered for load fluctuations at a frequency above 1 Hz.



Ramp support: The ramp support application uses the battery system to increase the response time of the overall system. Batteries can almost instantaneously deliver power compared to diesel engines or generators.



Appendix D : FLEXSHIP sister project

Start date: January 2023

End Date: December 2026

Type of Project: Horizon Europe research and innovation program under grant agreement N° 101095863 (HORIZON-CL5-2022-D5-01-01 Call)

Project Coordinator: Brussels Research and Innovation Center For Green Technologies

Summary: FLEXSHIP will facilitate the transition of the waterborne sector towards climate neutrality by delivering a digital green concept for electrification of vessels; this consists of a green digital twin (GDT) for designing fit for purpose vessel electrical grid architectures and integrating a large battery capacity system into two existing vessel electrical systems, a compact, low-weight, modular and simple, high-efficiency battery system, and a safe integration guide of the system onboard ensuring system interoperability.

Main Objectives:

- Define and formulate relevant KPI to achieve green, low-noise and sustainable ship propulsion with batteries. KPIs will be defined based on international regulations, requirements, and class notations.
- Analyse the defined KPI that allows credible consolidation that the electrification and hybridisation of the fleet is a real and achievable goal in the short term.
- Identify and establish all the necessary specifications and electrical requirements to carry out the integration of battery systems over a wide range of vessel types ; also identify the requirements for chargers in ports (shore to ship) and offshore.
- Determine the types of vessels in terms of ship mission, profile, size, and location which are going to be suitable for the implementation of the solutions that are going to be developed in FLEXSHIP.
- Identify all the applicable standards and regulations (international and European) for the battery integration and electrification of the fleet of small, medium and big sized ships. Analysis of the possible gaps that must be solved for the proper integration and approval/certification.

Topics related to NEMOSHIP goals:

Technical topics: EMS/BMS, ESS integration in the vessel

Project Website: https://www.flexship-project.eu/

The objectives will be achieved by 8 WP and 16 partners within 48 months. The project goals include the identification of specifications and requirements, the design and optimisation of the vessel's electrical architecture using the green digital twin, and the development and optimisation of individual components and subsystems. The system will then be tested at the component/subsystem level using hardware-in-the-loop and software in the loop tests. In the following phases, the entire FLEXSHIP system will be tested in two demonstrations over a minimum sailing distance of 150nm, followed by a 300nm contribution by the green digital twin to analyse sustainability and develop a business plan. Finally, the project will evaluate the system's full potential through an exploitation strategy, aiming to bring innovations from TRL4/5 to TRL7, which signifies a significant technological development.