D1.1 Review of energy storage technologies with relevance to marine applications and summary of use cases

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Lead Participant	University of Birmingham (UOB)	**Lead Author**	Faysal Hardan
Contributors:	Skeleton (SKT) Sintef Energy (SE), Sintef Ocean (SO), ASG Superconductors (ASG), Vard Electro (VE), Vard Design (VD), RINA Germany (RGER)	**Reviewers:**	Daniele Bosich, University of Trieste (UniTS), Pietro Tricoli, University of Birmingham (UOB)

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1 Table of contents

2 Introduction

The first work package (WP1) in the V-ACCESS project is setting the foundation for the further activities in the project by reviewing the state of the art of energy storage systems and identifying relevant use cases that should be considered. This report summarises the main results from the activities in WP1, including review of long-term and short-terms energy storage technologies and their use cases in marine vessels. The document contains first a review of energy storage systems especially towards hybrid storage systems combining more than a storage technology. Indeed, combining energy storage technologies with high energy density together with technologies of high-power density could potentially reduce the overall size and costs of the combined storage system onboard. Further, the document covers the selection of vessels that could be adopted as relevant use cases for the implementation of hybrid storage technologies and the rationale for their choice.

The shipping industry is responsible for a significant percentage of global greenhouse gas emissions, which resulted in a growing need to reduce emissions from shipping. The move towards sustainable energy has led to the development of electric vessels. Electric vessels, whether they are ships, boats, or ferries, provide a clean and efficient alternative to traditional fossil-fuel powered vessels. Such watercrafts are mainly based on Li-ion batteries to power the vessel's propulsion systems and its service and dynamic loads. Current development and advancement in short-term energy storage systems are paving the way towards more efficient and environmentally friendly solutions. When used onboard ships in combination with Li-ion batteries, or with future advanced batteries, they can lead to optimally sustainable design for future vessels. As such, the short-term energy storage systems can deliver/draw the peak/transient load power, leaving the long-term ESS as prime mover to only supply the total average power consumed by the vessel for longer service life of the long-term ESS, mainly lithium-ion batteries.

In this reports, two short-term energy storage systems are mainly reviewed, namely ultracapacitor energy storage and superconducting magnetic energy storage systems. The report also covers their potential applications onboard vessels in general, as well as their characteristics as short-term energy storage systems with high-power density for peak power shaving. However, before covering these aspects, the report starts with short review of different types of lithium-ion batteries for use onboard electric ships, including their characteristics and comparison amongst various types of their chemistries.

To support the selection process of the most appropriate type of energy storage system, the document reports on the analysis of potential suitable cases based on the typical power profiles and the presence of power peaks. The process started with shortlisting a few vessel types based on qualitative considerations. This is then refined with a quantitative assessment that demonstrates where a hybrid storage system can result in a more beneficial configuration.

3 Abbreviations and acronyms

BESS	Battery Energy Storage System
BoL	Beginning of Life
DoD	Depth of Discharge
DP	Dynamic Positioning
EoL	End of Life
ESS	Energy storage system
EMS	Energy Management Strategy
FC	Fuel Cell
HESS	Hybrid Energy Storage System
HP	High Power
KPI	Key Performance Indicators
LiB	Lithium-ion Battery
LiC	Lithium-ion Capacitor
OSV	Offshore Service Vessel
PSV	Platform Supply Vessel
SC	Super Capacitor
SMES	Superconducting magnetic energy storage
TRL	Technology readiness level
TSHD	Trailing Suction Hopper Dredger
UC	Ultra-capacitor
UCES	Ultra-capacitor Energy storage System
ZEWT	Zero-emission waterborne transport

4 Review of electrical energy storage technologies

This section reviews the main types and characteristics of the ESS that could be most interesting for maritime applications. The report starts with a review of lithium-ion batteries (LiBs) and emerging battery technologies for use onboard electric ships, including a comparison for different chemistries. Then a review of the characteristics of UCES and SMES is presented, discussing the main differences with batteries. Finally, the section presents a quantitative comparison between LiBs, UCES, and SMES.

4.1 Lithium-ion batteries

LiBs are the most common type of batteries that are used in electric and hybrid vessels, due to their high energy density, relatively long cycle-life, and low maintenance requirements [1]. However, not all lithium-ion chemistries or types of batteries are created equal and understanding the advantages and drawbacks of each type is crucial when choosing the right battery for an electric vessel [2], [3]. Various types of LiBs with different chemistries have been reviewed in the literature, but their reported properties, characteristics and parameters can vary and overlap widely, which make the accurate comparison between them difficult. The following table qualitatively compares the properties and advantages of five different types of Li-ion batteries that can be used for electric vessels [2], [3].

TABLE 4.1: QUALITATIVE COMPARISON BETWEEN DIFFERENT TYPES OF LI-ION BATTERIES

Battery type	Energy density	Power output	Lifespan	Thermal stability	Cost
Lithium Cobalt Oxide (LCO)	highest	low	short	low	relatively inexpensive
Lithium Manganese Oxide (LMO)	high	high	short	low	affordable
Lithium Nickel Cobalt Aluminium Oxide (NCA)	highest	high	long	low	affordable
Lithium Iron Phosphate (LFP)	low	highest	longest	highest	inexpensive
Lithium Titanate (LTO)	low	high	longest	highest	expensive

A more detailed description about Li-ion battery chemistries is reported in Appendix A. Table 4.1 shows that all five lithium-ion chemistries have advantages and disadvantages, and choosing the right one depends on the specific needs of the vessel. LCO batteries are a good choice for applications that require high energy stored in a small space, but they are prone to a high risk of thermal runaway due to the low thermal stability. LMO batteries offer a good balance between high energy density and high-power density, but they have a lower energy density compared to other chemistries. In comparison, NMC batteries offer a good balance between high energy density and high-power density and are relatively inexpensive, but they have a lower energy density compared to NCA batteries, which offer a very high energy density and high-power output, but they are relatively expensive and have a high risk of thermal runaway. Notably, LFP batteries offer a high level of output power, safety, and stability, but they have a lower energy density compared to other Li-ion chemistries. Another type is the LTO batteries which provide the highest thermal stability with longest lifespan, but its low energy density makes it undesirable for onboard application as it brings extra weight to the vehicle. As lithium-ion technology continues to advance, new chemistries and types of batteries may emerge that offer even better performance and safety characteristics.

In general, the more power capability is considered for battery design, the larger the size of the battery electrodes should be considered, which also lead to reduction in the average value of internal resistance of the battery. This also depends on the Li-ion battery chemistries that can be illustrated through the following table, which summarises the internal resistance variation of Li-ion battery cells with three different chemistries [4].

Table 4.2: Internal resistance of Li-ion battery cells for three different chemistries

Battery type/chemistry	Lithium Iron Phosphate - LFP	Lithium Nickel Cobalt Aluminium Oxide - NCA	Lithium Nickel Cobalt Manganese Oxide - NMC
Cell internal resistance (mΩ)	40	79	75
Specific Energy (Wh/kg)	110	260	220
Cell voltage (V)	3.2	3.6	3.7

It is important to note that the internal resistance values listed in the table are general ranges and may vary depending on the specific battery model and manufacturer. Additionally, other factors such as the size and complexity of the battery pack, the age and condition of the batteries, as well as the specific application may also affect their internal resistance.

4.2 Emerging battery technologies

Conventional batteries have several inherent limitations like a short lifespan and low energy density in general. These obstacles have led researchers to seek more powerful and efficient batteries, exploring new chemistries and technologies. The new technologies for batteries currently being researched are:

a. Solid-State Batteries

These batteries use a solid-state electrolyte that eliminate the liquid component of conventional batteries, which increases their safety significantly. They also have increased energy density, faster re-charging, and longer life span [5].

b. Lithium-Sulphur Batteries

These batteries are gaining attention for their higher energy density and lower cost, as compared to lithium-ion batteries [6], [7]. They can store almost five times the energy of a lithium-ion battery in the same volume, making them suitable for powering electric vehicles, unmanned aircraft vehicles, electric vessels and other high-energy-demanding applications.

c. Sodium-Ion Batteries

These batteries offer a low-cost and use sulphur as the charge carrier instead of lithium. Sulphur is significantly more abundant than lithium and this reduces cost and carbon emission related to the supply chain. They can remarkably outperform Li-ion batteries from safety and low operational temperature point of views, but they still have a slightly lower efficiency [8].

d. Metal-air batteries

These batteries are an intermediate between fuel cells and normal secondary cells, because the reactant is not part of the cell and instead a flow of air is circulated to the positive electrode of the battery to provide the oxygen for the reaction. Their energy density is theoretically 3,500 Wh/kg, [9] albeit practical realisation will be expected to be in the range of 950-1,100 Wh/kg [10].

However, the development of advanced batteries is still in its early stages. Manufacturing, scalability, and the cost of these batteries still need to be addressed to make them a widely available and feasible alternative for the state-of-the-art Li-ion batteries. Moreover, better regulatory capabilities need to be introduced to ensure the safe disposal and recycling of advanced batteries.

4.3 Ultra-Capacitor Energy Storage (UCES)

UCES is a type of short-term energy storage system based on ultracapacitor cells that store energy in an electric field between two electrodes. An ultracapacitor cell uses porous materials that allow for a large surface area, which increases the amount of energy that can be stored. Whereas LIBs store energy chemically in intercalation and insertion materials, UCs store energy physically in form of surface charges within the electrochemical double layer. The main types of ultracapacitors (UCs) are:

a. Electrochemical Double-Layer Capacitors (EDLCs):

EDLCs store energy by separating positive and negative charges across an electrolyte in the order of 0.3–0.8 nm, that is much smaller than conventional capacitors. EDLCs typically have higher capacitance values but lower voltage limits compared to other types of capacitors [11], [12].

b. Pseudo-capacitors:

Electrochemical pseudo-capacitors use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudo-capacitance additional to the double-layer capacitance. This is accomplished through a process known as electro-sorption, reduction-oxidation reactions, and intercalation processes, termed pseudo-capacitance. Pseudo-capacitors have higher energy density than EDLCs but lower than batteries. An example of a pseudo-capacitor is a redox reaction where the ion is O2+ and during charging, one electrode hosts a reduction reaction and the other an oxidation reaction. Under discharge the reactions are reversed. Unlike batteries, in faradaic electron charge-transfer ions simply cling to the atomic structure of an electrode. This faradaic energy storage with only fast redox reactions makes charging and discharging much faster than batteries.

c. Hybrid ultra-capacitors:

Hybrid capacitors combine the properties of EDLCs and batteries. They use electrodes with differing characteristics: one exhibiting mostly electrostatic capacitance and the other mostly electrochemical capacitance. In other words, they consist of an EDLC electrode and a pseudocapacitive electrode [13], [14]. An example of a hybrid capacitor is a lithium-ion capacitor (LiC), in which the anode is the same used in lithium-ion batteries and the cathode is the same used in EDLCs.

d. Asymmetric ultra-capacitors:

Asymmetric ultra-capacitors use different electrode materials, typically combining carbon-based electrodes with a high-capacity electrode material [15]. This configuration allows for increased energy density compared to symmetric ultra-capacitors.

4.3.1 Characteristics of UCES

Due to the physical energy storage mechanism, UCs can be charged and discharged within less than a second for over 1,000,000 times, even at temperatures ranging from -40°C to +65°C. This is because UCs are not limited to the velocity of chemical reactions typical of batteries and the degradation of materials. However, due to only using surface effects for energy storage, classic UCs are limited in their energy density by the amount of available surface area in their electrodes. New materials like curved graphene have a larger available surface area, microporosity, and electric conductivity than activated carbons. The energy density increases from 4-6 Wh/kg to more than 10 Wh/kg while maintaining power densities above 30 kW/kg that are approximately 100 times higher than LiBs. This makes them ideal for applications where a quick response with power peak is required, such as power quality and peak-power shaving applications. Round-trip efficiencies are also higher than LiBs on average and it is around 95% [16], mainly due to very low equivalent internal resistance (ESR).

Other important characteristics of UCES are the low maintenance, as they are essentially static systems, and high safety as there is no risk of thermal runaway typical of LiBs, with consequent reduced risk of toxic fumes. Finally, the materials involved in the construction do not present criticalities in terms of abundance and carbon emissions of the supply chain.

Since the voltage of UCs changes considerably during charge or discharge, a power converter is always needed to match the UC output voltage with the voltage of the power system. The topologies of power converters used for UCES systems includes buck converters, boost converters, buck-boost converters, and dual active bridge converters [17]-[19], as described in Appendix A. These converters are voltage-source because UCs electrically behave like capacitors and are current-controlled when connected to the shipboard power system.

4.4 Superconducting Magnetic Energy Storage (SMES)

SMES stores energy in the magnetic field of a superconducting coil, which has near zero resistance to electrical current flow when cooled to extremely low temperatures. The energy stored in the magnetic field of the coil can be released quickly to provide high-power output. The SMES systems can have a relatively moderate energy density, long lifespan, and fast power response, making them ideal for use in high-power pulse applications such as power quality control and grid stabilization in response to variable load.

Several superconducting materials have been used or proposed for SMES systems [20 - 25]:

a. Magnesium-diboride (MgB_2)

This is an intermetallic compound that has a critical temperature of 39K and a critical magnetic field of 74T. It is relatively cheap and easy to fabricate, but it has a moderate mechanical strength and a high sensitivity to strain. They can be produced with "react in wind" technology that means there is no heat treatment required on the coil to get the superconducting properties. This makes it easy to manufacture the coils like for other technology, e.g., copper coils. Its high operating temperature associate to a relative isotropy makes it a good candidate for SMES.

b. Niobium-tin (Nb_3Sn)

This is also an intermetallic compound that has a critical temperature of 18.3K and a critical magnetic field of 30T. It is widely used for high-field magnets, but it has a brittle nature and a low tolerance to thermal cycling. The material requires liquid Helium at 4.2 K to be superconducting, like NbTi, and can reach higher magnetic fields. Only “wind and react” technology can be used and a real attention to the manufacturing has to be paid. Heat treatment of the coils need several weeks at 700°C which makes the insulation of the coils difficult to achieve.

c. *Niobium-Titanium (NbTi)*

Commercially available for SMES use. When operated at 4.4K, it can carry current up to 2000A/mm^2 at a magnetic field of 5T, which is more than 100 times greater in comparison to copper at typical operating current density [26]. SMES units based on this material must use liquid helium to keep the coil of Niobium-Titanium at 4.2K, which is the temperature required for the material to become superconducting. For this type, the low operating temperature makes the cooling expensive and relatively inefficient especially for charge/discharge phases that require extra cooling power. This makes the solution probably not affordable.

d. Rare-earth barium copper oxide (ReBCO)

This is a family of copper-based oxide ceramic materials which have a critical temperature of 95K and a critical magnetic field of 120-250T. It is one of the most promising types of high-temperature superconductors, but it has a complex fabrication process and a high anisotropy.

Generally, an SMES system can be divided to three main parts, as illustrated in Fig. 4.1:

- The superconducting coil: it is made by winding superconducting wires. Depending on the operating temperature, magnetic field and current, it is possible to use low temperature superconductors (LTS), like NbTi or Nb_3SN, and high temperature superconductors (HTS), like ReBCO and MgB_2. HTS can be operated at high magnetic field (> 4T) and high current, but it is still expensive and produced in short lengths of

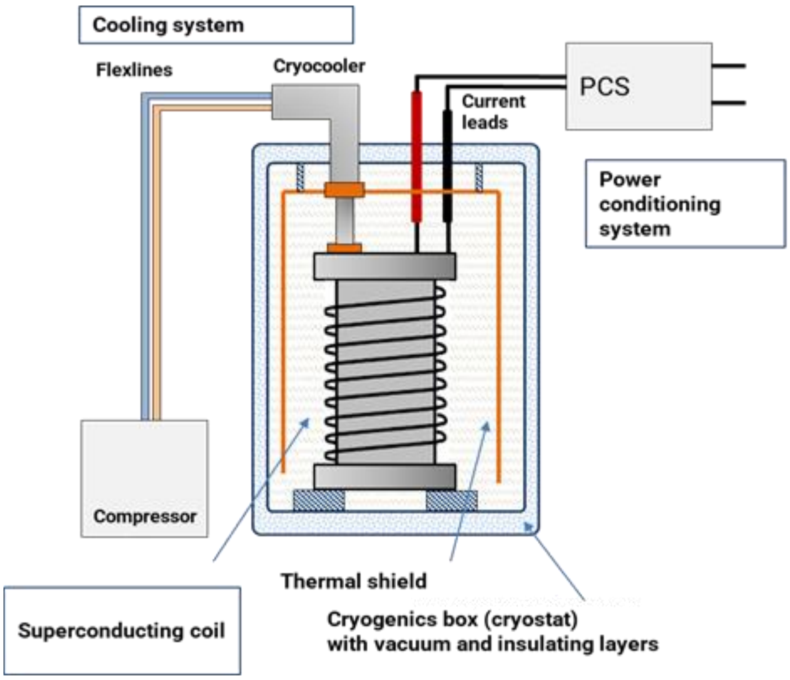


FIG. 4.1: GENERAL SMES STRUCTURE WITH A DRY COOLING SYSTEM

about 200m, whilst MgB_2 can operate at intermediate field (less than 2T), is cheaper, and can be produced in long lengths. Ultimately, the LTS MgB_2 offers the possibility to use simplified cooling systems without the need for cryogenic liquid.

- The cooling system: since the superconductor coil acquires superconductive properties at cryogenics temperature (around 20K for MgB_2), the cooling system must be designed to maintain the coil at this operating temperature. In a system without cryogenics liquid (liquid He or N_2) this is done using a "cryocooler", and the heat is removed by conduction (a cold plate is attached to the coil). Cryocooler needs additional components and equipment, namely a compressor with flex lines and a chiller. Furthermore, the superconductor coil has to be thermally insulated from any external heat source, so it is confined in a "cryostat" - a stainless steel box with a vacuum between its walls.
- The power conditioning system (PCS): a DC/DC or DC/AC power-electronic converter that interfaces the SMES system to the power system is needed to condition the power delivered/absorbed by the SMES. The main feature of the power converter is that the first stage must be current-source type, as SMES have electrical characteristics of inductors. Therefore, to be interfaced with a shipboard power system operating at constant voltage, a second voltage-source stage is normally required.

4.4.1 Characteristics of SMES

SMES have a very high-power density compared to LiBs and make them preferable for applications that require high-pulse power where space is limited. Similar to UCES, SMES have a very fast response-time and they can be discharged in less than a second. The life cycle is very long and SMES can be charged/discharged millions of times without degradation in performance. The superconducting coil is very durable and does not require regular maintenance, with an expected lifetime longer than 25 years. The compressor includes moving parts and requires a regular maintenance cycle. SMES have a round-trip efficiency of around 90%, [27], mainly due to the energy dissipated by the cryogenic system and the power converter.

The energy density of SMES is considerably lower than LiBs and even lower than UCES due to the cryocooler and the cryostat. These two components account for more than 80% of the total SMES volume, using for referenced medium size system of 500kJ [28].

Therefore, the SMES system is more suitable in an environment where the weight is not an issue, or where cryogenic system is already available. For instance, there is an increasing interest in powering ships using hydrogen which can be liquified and stored aboard (LH2). Hydrogen is liquefied at 20K, which is the temperature suitable to make an MgB_2 or ReBCO coil superconductive. If the superconducting coil is placed inside the LH2 tanks, the cryogenic system of the SMES would not be needed, significantly increasing the energy and power densities of the SMES.

Also, SMES systems have typically a bespoke design on the basis of a specific application. This can be an advantage because a single system can be designed up to MW power and operate at high voltage. However, the system is less modular that LiBs and UCESs and it is more difficult to adapt it for different applications.

4.5 Comparison of Energy Storage Systems

The table below covers data for the most important characteristics of the UCES and SMES, and Li-ion batteries for the purpose of quantitative comparison [29 – 32]. This table has been also filled using data from real UCES and SMES developed by Skeleton and ASG, respectively. The data of the reference devices are reported in the Appendix A.

TABLE 4.3: CHARACTERISTICS OF UCES, SMES, AND LIBs

Characteristic	UCES	SMES	LIBs
Specific Energy (Wh/kg)	1.5 to 10	< 1	100 to 265
Specific power (W/kg)	2k to 10k	1k	0.3k to 1.5k
Voltage per-cell [V]	1.5 to 3 V	Custom module up to several kV per module	2.5 to 4.2 V
Equivalent series resistance (ESR) (mΩ)	0.1 - 0.2 / cell	~0	18 / cell
Round-trip efficiency at nominal current (%)	95	~90	90-95
Charge/discharge cycles	100k – 1000k	> 1000k	0.5k – 7k
Self-discharge	days - weeks	hours – days or even months (depending on current-cycle power losses)	months
Charge/Discharge Rate, C (W/Wh)	1,250 - 1,500 C	>1000 C	1 - 6 C
Charging time	1s to 30s	approx. 1s	20min to 120min
Potential EMI issues	N/A	High magnetic fields	N/A
Health and safety risks	Flammable electrolyte, liquid leaks	Exposure to magnetic flux density, liquid leaks	Flammable electrolyte, liquid leaks, thermal runaway

The table shows that UCES and SMES have similar characteristics in terms of energy density, albeit UCES have slightly higher values. Albeit not shown in the table, it is widely reported that the power density of

SMES is similar to UCES and, hence, both are suitable for application where high-power is required for short-term energy delivery.

Both UCES and SMES have a lifespan much longer than batteries. However, SMES need several auxiliary systems that can reduce their reliability and increase maintenance costs. UCES are simpler, but forced air cooling or liquid cooling might be needed in confined spaces like vessels, making the need for maintenance closer to that for SMES.

UCES are based on low-voltage low-energy cells, similar to batteries. Therefore, UCES for vessels would include a large number of cells in series and several strings in parallel to reach the required voltage and power levels. Conversely, SMES are typically bespoke so that a single coil would be designed for the required voltage and power. This can potentially have a weight and volume advantage compared to UCES and LiBs, especially for the typical power-levels of vessels. On the other hands, each SMES should be designed for a specific application, while UCES and LiBs are more modular.

Furthermore, ultracapacitor cells, like LiBs, do not have particular issues with EMI, as they accumulate energy in electric field at low voltage. During charge/discharge, the variation of the electric field must be verified to check for EMI with other nearby objects. SMES are designed with a single coil, so the magnetic field can be intense and need to meet the existing limits on maximum public exposure of 118mT for frequencies lower than 0.153Hz [33].

In terms of safety, the main risks of UC are similar to batteries as the electrolyte is flammable, and the liquid can leak in case of mechanical damage. However, UC are not exposed to thermal runaway, that is typical of LiBs, because of the reduced amount of chemical reaction occurring at their electrodes. Risks from leaks are also present for SMES in the cryogenic liquid, albeit this could be mitigated using direct cooling.

5 Screening of candidate vessels for hybrid storage technologies

Table 5.1 shows the summary of typical ESS technology requirements for different marine application reported by DNV-GL in [34]. From Table 5.1, it can be noted that relevant HESS marine applications may include ferries, offshore drilling units, bulk vessels with cranes, high speed ferries, fishing vessels and fish farms vessels as they typically require both high c-rates and high number of cycles.

On the other hand, Table 5.2 shows the types of battery requirements per vessel type as reported in [35], where two types of operations are analysed for each vessel: the primary operation representing the most common types of cycles that a vessel will perform with the installed battery system, and the secondary operation are the operations performed with the batteries that are not according to the average design conditions.

TABLE 5.1: SUMMARY OF TYPICAL ESS TECHNOLOGY REQUIREMENTS FOR DIFFERENT MARINE APPLICATION [34]

Ship type	C-rate	Cycles	Energy	Technology
Ferry	Very high	Very high	Nominal	NMC, LFP, LTO
OSV	Very high	Very low	Nominal	NMC, LFP, LTO
Cruise	Low	Likely high	Very high	NMC, LFP
Offshore drilling unit	Very high	Variable	Low	NMC, LFP, LTO, supercapacitors
Fishing vessel	Nominal	Nominal	Nominal	NMC, LFP, LTO
Fish farm vessel	Nominal	Nominal	Nominal	NMC, LFP, LTO
Shuttle tanker	Very high	Very low	Nominal	NMC (power), LTO
Short sea shipping	Highly variable	Highly variable	Highly variable	NMC, LFP, LTO
Deep sea vessels	Highly variable	Highly variable	Highly variable	NMC, LFP, LTO
Bulk vessels with cranes	High	High	Low	NMC, LFP, LTO
Tugboats	Highly variable	Highly variable	High (minimal space)	NMC, LFP, LTO
Yachts	Low	Low	High	NMC, LFP, LTO
High speed ferry	High	High	High	NMC, LFP, LTO

Wind farm support vessels	Very high	Very low	Nominal	NMC, LFP, LTO

TABLE 5.2: TYPES OF BATTERY REQUIREMENTS PER VESSEL TYPE AS REPORTED BY SEABAT [35]

Vessel	Application	Primary C-rates	Primary Cycles/day	Secondary C-rates	Secondary Cycles/day
Fishing vessel 1	Full electric	<1C	<1	<1C	<1
Fast Crew Supplier	Full electric	<1C	<1	<1C	<1
Inland container vessel	Full electric	<1C	<1	<1C	<1
Small tug	Full electric	<1C	<1	<1C	<1
Yacht	Full electric	<1C	<1	<1C	<1
Fast Crew Supplier	Full electric	<1C	1 → 3	<1C	<1
Fast Ferry	Full electric	<1C	> 7	<1C	<1
Cable lay vessel	Load levelling and spinning reserve	1C → 3C	<1	<1C	<1
Hybrid tug	Full electric	1C → 3C	<1	1C → 3C	<1
Patrol vessel	Full electric	1C → 3C	<1	1C → 3C	<1
Fast Crew Supplier	Peak shaving and spinning reserve	1C → 3C	<1	> 6C	<1
Fast Crew Supplier	Full electric	1C → 3C	3 → 7	3C → 6C	1 → 3
Ferry	Full electric	1C → 3C	> 7	1C → 3C	<1
Shoal buster	Boost function	3C → 6C	<1	1C → 3C	<1
Harbour tug 1	Boost function	3C → 6C	1 → 3	<1C	<1
Harbour tug 2	Full electric	3C → 6C	1 → 3	1C → 3C	<1
Fishing vessel 2	Spinning reserve	3C → 6C	1 → 3	3C → 6C	<1
Cruise vessel	Full electric	3C → 6C	3 → 7	1C → 3C	1 → 3
Urban ferry 1	Full electric	3C → 6C	3 → 7	3C → 6C	<1
Ro-Ro ferry 1	Full electric	3C → 6C	> 7	1C → 3C	<1
Waterbus 1	Full electric	3C → 6C	> 7	1C → 3C	<1
Waterbus 2	Load levelling	3C → 6C	> 7	1C → 3C	<1
Fishing vessel 3	Peak shaving and boost function	3C → 6C	> 7	1C → 3C	1 → 3
Ro-Ro ferry 3	Load levelling and boost function	3C → 6C	> 7	1C → 3C	1 → 3
Ro-Ro ferry 4	Full electric	3C → 6C	> 7	1C → 3C	1 → 3
TSHD	Peak shaving	> 6C	<1	3C → 6C	<1
Harbour tug 3	Boost function	> 6C	1 → 3	1C → 3C	<1
Fish carrier	Peak shaving and spinning reserve	> 6C	> 7	3C → 6C	<1
Urban ferry 2	Full electric	> 6C	> 7	3C → 6C	<1
Ro-Ro ferry 2	Full electric	> 6C	> 7	> 6C	3 → 7

5.1 Vessel functions that may benefit from hybrid storage support

The data in Tab. 4.3 clearly shows that both UCES and SMES are not well suited for applications where a long-term delivery of energy is required. Therefore, it is unlikely that they are used alone for the propulsion of electric vessels, apart from specific cases where the sailing distance is very short and the number of trips per day are very high (for example the Ar Vag Tredan). However, there are a number of other applications where they could be used in combination with diesel engines and/or batteries to form hybrid energy storage (HESS), as described here.

1. Back-up power

A lot of critical equipment onboard marine vessels cannot be left without power, even if for short amount of time. Having a back-up system is mandatory, as it allows to entirely ride-through short power outages without effects, or (in case of long outages) to safely shut-down the equipment in a manner that allows the easiest restoration of operations subsequently. For this application, a high-energy density is desirable to reduce the space needed for the back-up power supply as well as a fast response.

2. Peak power shaving

In marine offshore operations (especially in rough sea conditions), loads are often intermittent and characterized by several high peaks of power which put stress on the generators and accelerate their wear. Moreover, these rapid increases in load can cause genset protections to trip and generate cascade blackouts on the ship. Energy storage can be used for power support, and they require a charge/discharge cycle of 1-20s with a large number of cycles per day.

3. Active heave compensation (AHC)

AHC is the precise control of the vertical position of some payload (for instance, a pump or a drill) held by a crane, also in presence of waves and wind. This involves a periodic movement characterized by short power cycles of high peak power consumption and regeneration, which can cause stress on the vessel power system.

4. Motion compensation

Motion compensation is similar to AHC, pile gripper ships and other offshore vessels require to hold a load in still position (for example a wind turbine mast which needs to be planted in the sea bottom). Without compensating for the horizontal movement of the vessel, this task would be impossible. Electric drives are normally used to control the movement, which requires high peak power.

As all the power used come from gensets, energy storage allows to reduce the sizing of the generators while allowing them to work in smoother manner. This saves fuel and increase the life expectancy of the engines, while reducing part of the electrical installation cost.

5. Parallel hybrid propulsion

Ships which operate in adverse sea conditions, experience fluctuating load on the propellers and shafts due to the waves. The size of the ship compared to the waves influences the overall effect, however the fuel consumption during cruising and manoeuvring is increased by up to 20% compared to calm water condition. Therefore, the adoption of energy storage would enable fuel saving of up to 20% and longer engine lifetime.

6. Engine gradient support

Marine vessel, especially in Oil & Gas and offshore operations, are equipped with pumps and other highly discontinuous loads. This generates step loads on the power distribution, which can cause genset instability, especially when cleaner fuels such as LNG is used. To increase the stability of the power system, slow responding gas-engines can be enhanced with fast reacting energy storage, which in addition reduces the fuel consumption due to smoother operation of the gensets.

7. Floating cranes

Floating cranes operate in harbours and serve a variety of purposes, among which material handling, engineering works, bridgebuilding, port construction etc. They run on diesel generators, but these are extremely oversized to handle the highly variable loads, which causes high fuel consumption. Energy storage allow to recover energy during the lowering of the load, instead of being dissipated by a brake. Energy storage for this application would need to operate with short cycles and large amounts of energy, with cycles repeated many times per day.

8. Engine start

Generators (using diesel, but more and more natural gas) are the main power source and need to be cranked reliably. Lead acid batteries are still used today to provide these gensets with the high current needed to crank, but they require frequent replacement and maintenance, and are the main source of failure in starting a genset.

5.2 Candidate vessels for hybrid storage technologies

5.2.1 Stern trawler

A stern trawler is a vessel mainly used for fishing and its typical operating cycles include high power peaks during shooting and heave of the trawl. A rendering of the vessel is shown in Fig. 5.1.

FIG. 5.1: RENDERING OF SHIP TYPE 'STERN TRAWLER' – CREDIT VARD DESIGN

The use case is modelled on the basis of a stern trawler designed by Vard Design, with the main characteristics reported in Table 5.3.

TABLE 5.3: STERN TRAWLER - KEY VESSEL FEATURES

Type of Vessel	Stern Trawler	LOA (m)	80m
Class Society	DNV	Breadth mld (m)	17m
Class Rule Edition	NN		

The stern trawler is equipped with Vard Electro's SeaQ Micro Grid, which enables variable rpm on the main engine while the shaft generator provides a stable voltage and frequency to the vessel's electrical systems. Converters for the electric winches are directly connected to the SeaQ Micro Grid. In addition, the vessel has an integrated energy storage system, and has options for both battery operation, diesel-mechanical and diesel-electric propulsion.

5.2.2 Ferry

The ferry is equipped with battery packs on board that can be charged from the mains (plugin hybrid electric). Table 5.4 summarizes the key features of the vessel.

The ferry meets strict environmental requirements, which means extensive reductions in CO_2 emissions, fuel consumption and energy use. They must be very energy efficient with good seaworthiness and maneuverability. The ferry is used for commuting between two quays with around 30 minutes of travelling time. Power peaks are expected from maneuvering of the vessel in port.

TABLE 5.4: FERRY - KEY VESSEL FEATURES

Type of Vessel	Ferry	LOA (m)	74m
Class Society	DNV	Breadth mld (m)	15m
Class Rule Edition	NN		

5.2.3 Platform supply vessel

A platform supply vessel (PSV) is a ship specially designed to supply offshore oil and gas platforms and other offshore installations. They are characterized by a large open deck area to store supply and equipment. A rendering of the vessel is shown in Fig. 5.2, while its main characteristics for the case study are shown in Table 5.5. Power peaks are expected for operations of the vessel close to offshore platform to actively maintain a certain distance using dynamic positioning.

FIG. 5.2: RENDERING OF SHIP TYPE 'PSV' – CREDIT VARD DESIGN

TABLE 5.5: PSV - KEY VESSEL FEATURES

Type of Vessel	Offshore supply ship	LOA (m)	94m
Class Society	NN	Breadth mld (m)	21m

Class Rule Edition	NN		

5.2.4 Gangway for windfarm vessels

Windfarm vessels are used to service offshore windfarms, as shown in Fig. 5.3. The gangway to reach the wind farm is electrically driven and powered by two DC buses, one from port side and one from starboard side for redundancy.

FIG.5.3: GANGWAY AT WINDMILL– CREDIT VARD DESIGN

5.2.5 Harbour tug

Harbour tugs carry out all towage services required on and around ports. They have to be highly manoeuvrable and with large power to assist large tankers and bulk Carriers in various port locations, as well as offshore projects. Therefore, they are characterised by highly discontinuous power requirements. The key characteristics of a harbour tug are reported in Tab. 5.6.

TABLE 5.6: HARBOUR TUG - KEY VESSEL FEATURES

Type of Vessel	Harbour tug	LOA (m)	32m
Class Society	NN	Breadth mld (m)	13m
Class Rule Edition	NN		

5.2.6 Live fish carrier

Live fish carriers are equipped with fish handling equipment that can draw significant power peaks. Additionally, they need a spinning reserve to smooth-out their power consumption. The key characteristics of a fish carrier are reported in Tab. 5.7.

TABLE 5.7: FISH CARRIER - KEY VESSEL FEATURES

Type of Vessel	Live fish carrier	LOA (m)	69.99m
Class Society	NN	Breadth mld (m)	12m
Class Rule Edition	NN		

5.2.7 Bulk carrier

Bulk carriers have onboard electric cranes for the handling of the load and these draw significant power peaks for a short time duration. Also, they need a spinning reserve to smooth out their power consumption. The key characteristics of a bulk carrier are reported in Tab. 5.6.

TABLE 5.8: BULK CARRIER - KEY VESSEL FEATURES

Type of Vessel	Bulk carrier	LOA (m)	147.66 m
Class Society	NN	Breadth mld (m)	21 m
Class Rule Edition	NN		

5.2.8 Cruise vessels

Cruise vessels can be designed with low carbon fuel, for example with fuel cell systems installed and designated for compliance with safety of life at sea (SOLAS) passenger ship requirements. This vessel is usually equipped with diesel electric hybrid propulsion with low C-rate and very high energy storage.

TABLE 5.9: CRUISE VESSEL - KEY VESSEL FEATURES

Type of Vessel	Cruise vessel	LOA (m)	240 m
Class Society	NN	Breadth mld (m)	32 m
Class Rule Edition	NN		

6 Quantitative assessment and selection of the case studies

One of the objectives in WP1 is to define relevant case studies for the application of combined energy storage technologies in low or zero emission vessels. As a first step, identification of marine applications that could be potentially benefit from the use of hybrid storage technologies has been undertaken based on a qualitative approach. Basically, marine applications where the ESS requirements are characterized by high C-rates and high number of cycles could be considered as potential candidates for the HESS case studies. Analysis of typical ESS technology requirements for different marine applications reported from DNV-GL in [34], and from SEATBAT project in [35], have been taken as initial input, as detailed in Appendix B. Feasible vessel types and applications for hybrid energy storage include full electric Ro-Ro ferries, full electric urban ferries, fish carriers with spinning reserve and peak shaving ESS functions, fishing vessels with spinning reserve and boost ESS functions, full electric waterbuses, full electric and hybrid harbour tugs with ESS boost function, and hybrid ro-ro ferries with load levelling and boost function.

Once the vessel types and their relevant HESS marine applications were identified, then the preselection of potential case studies was done based on two criteria: the availability of the required data for the different analysis intended to be performed by the other work packages, which constitute the definition of the case studies; and, a quantitative assessment based on simplify approach to identify relevant application profiles before the full definition of ship mission profiles and full HESS algorithm evaluation. The main propose is to provide a first screening of HESS solutions looking for potential gains in required installed energy and capital cost of HESS versus ESS solution based on single battery technology. The first screening has been performed considering one high-energy battery technology (NMC Li-ion) as base case technology for ESS solution and considering HESS as combination of that battery technology and two possible high power storage technologies: UCES and SMES.

The qualitative assessment is based on power profile time series as input. The marine profile data from three different sources have been considered: log data of relevant vessels provided by Vard, relevant power profile data from [35], and simulations of specific vessel applications/operations provided by SINTIF OCEAN. It should be mentioned that some limitation on granularity of the available power profile time series may hide some requirements relevant for application of HESS technology.

6.1 Methodology

Fig. 6.1 shows the HESS evaluation framework planned to be implemented within WP1 activities to provide a preliminary assessment of lifetime, cost and/or emission savings with utilization of combined storage solutions for the selected case studies. The main inputs for the HESS framework are the ship mission profile, general ESS specifications, and the core ESS technology performance parameters. The ship mission profile and general ESS specifications are part of the case study definition. The selection of the battery technology and HP-ESS technology for a given vessel type can be considered as additional degree of freedom in the algorithm. From the ship mission profile then the HESS power profile can be estimated. For the case of zero emissions (full electric) vessels, the HESS should provide the full load power defined by the ship mission profile, and together with the information about charging availability, then the HESS power profile can be estimated. On the other hand, for the case of low emissions vessels (hybrid marine power systems), the energy management strategy (EMS) for ship power system needs to be considered, where the intended ESS functionalities accounts for the estimation of the HESS power profile. The ship-EMS and the ESS functionalities brings additional degree of freedom to the algorithm, which allows to map the different trade-off between potential fuel savings and ESS requirements [36], [37].

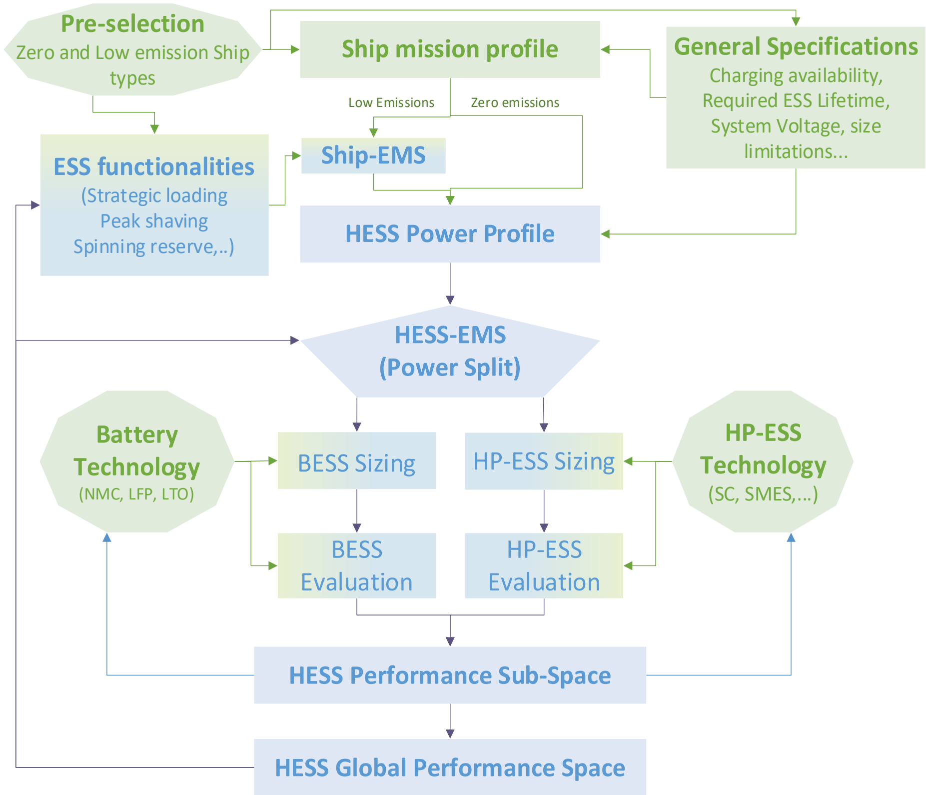


FIG. 6.1: HESS EVALUATION FRAMEWORK

Once the HESS power profile is estimated, the EMS for HESS will determine the way the power is split between the BESS and the HP-ESS, so the power, energy, and cycling requirements (given implicitly by the HESS power profile) are split into two power output profiles, for the BESS and the HP-ESS, and therefore, the requirements for each ESS subsystem can be estimated [38]. Here, an additional degree of freedom is added to the algorithm as different power split alternatives will end up in different ESS subsystem requirements and therefore different HESS solutions (combinations of installed capacity for BESS and HP-ESS).

After the power, usable energy, and cycling requirements for each ESS subsystem are established, then an ESS technology sizing estimation is performed, so the actual required energy capacity to be installed is estimated against the desired HESS design lifetime.

Finally, the complete evaluation of each ESS subsystem is performed by the BESS and HP-ESS evaluation algorithms, so the additional discrete components of each subsystem, like the power converters and/or cooling systems are considered to give an estimation of the performance of each HESS solution. The performance space includes the total capital cost, size (volume, weight), expected HESS lifetime, installed capacity and power capability, among others.

The relevant tasks associated to the implementation of the proposed HESS evaluation framework are summarized as following:

a. Marine application case definition - Ship Mission Profile estimation
b. Energy management Strategy for Ship power system
c. Energy management Strategy for HESS
d. Simplified ESS technology sizing and evaluation methodology.
e. Performance space definition and evaluation: Cost, size (volume, weight), expected HESS lifetime, emissions savings.

The proposed HESS evaluation framework could be used to compare different marine application case studies and therefore server as qualitative assessment in the process of selecting the case studies for V-ACCESS project. However, the selection of case studies needed to be done early in the project as many of the activities in other WPs depends on the case studies definition as main input, which gave not enough time to implementing the proposed HESS evaluation framework, therefore a simplified approach based on the proposed HESS evaluation framework has been proposed to get a first screening for HESS application profiles and therefore use it as qualitative assessment in the process of selecting the case studies for V-ACCESS project. Fig. 6.2 shows the simplified HESS evaluation framework for first screening, which aims to provide a fast way to detect relevant application profiles before the full definition of the ship mission profile and full HESS algorithm evaluation.

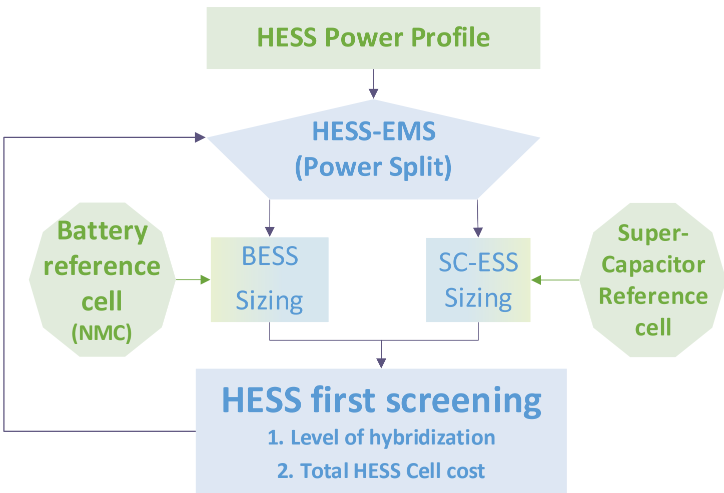


FIGURE 6.2: SIMPLIFIED HESS EVALUATION FRAMEWORK FOR FIRST SCREENING. NMC VS SC TECHNOLOGIES.

The approach in Fig. 6.2 does not consider all the degree of freedom as in Fig. 6.1, but focusing on comparing HESS versus BESS based on NMC battery technology. The optimization of the energy management strategy at ship power system level is neglected and therefore the HESS power profile needs to be provided to the algorithm. The HESS power profile could be estimated from preliminary ship profile data, which can be obtained from available log data, simulations or data reported in the literature. Also, the first screening considers one type of battery technology, and focusing on technologies with high energy density, the NMC battery technology has been considered.

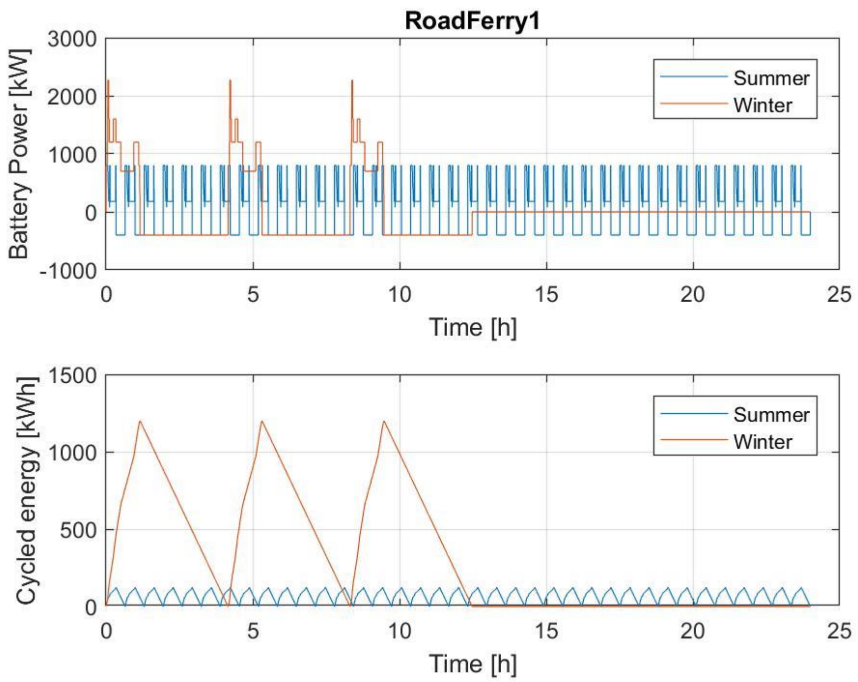
The methodology adopted to provide the first screening for HESS application profiles is composed by mainly four processes, which are summarized as following:

a. HESS Power profile: Definition of the power time series to be supplied by the ESS and its number of yearly operational cycles.
b. HESS Power Split: Algorithm to split the required power between the BESS and the HP-ESS, so the power, energy, and cycling requirements (given implicitly by the HESS power profile) are divided into two power output profiles, therefore the minimum requirements per ESS can be estimated.
c. ESS Sizing: This process aims to estimate the required energy to be installed per ESS to fulfil the minimum requirements accounting for ESS technology performance and design lifetime.
d. HESS first screening: To map HESS solutions looking for potential gains in required installed energy and capital cost of HESS versus BESS.

6.1.1 HESS Power Profile

The HESS power profile is defined by the ship mission profile, which depends on each marine application. In general, the HESS power profile can be composed by N_{ts} power time series, each with an associated expected operating days per year. Different power time series will represent different operations through the year, which can be associated to seasonal variations and/or possible changes in operative conditions.

Fig. 6.3 shows an example of HESS power profile for a full electric Ro-Ro ferry, which is reported in (SEABAT, 2021). The Ro-Ro ferry mission profile has two main representative power profile operations, which corresponds with seasonal variations in the route for summer and winter. The summer profile, happening 335 days per year, when there is no ice, the ferry makes 37 crossings per day. During the heavy part of the winter, occurring 30 days per year, when there is ice, the ferry makes only 3 crossings per day on a different route which require significantly more energy. Fig. 6.3 shows the daily power time series for both, summer, and winter profiles, where the positive power represents the discharge power from the HESS. A 400-kW



charger is available at each ferry station, so the HESS recharge the energy consumed after each trip section. The cycled energy, estimated from the power time series is also shown in Fig. 6.3.

By analysing the HESS power profile presented in Fig. 6.3, it is possible to establish that the Ro-Ro ferry needs a minimum energy of 124 kWh for summer operation and 1,200 kWh for winter operation. Also, the HESS needs to be able to provide at least a maximum discharge power of 800 kW for summer profile, while for winter operation requires 2,270 kW. Also, the system should be able to charge at least 400 kW continuous power. Regarding the cycling requirements, the HESS is required to perform 90 cycles of 1,200 kWh (related to winter operation), plus 12,395 cycles of 124kWh (related to summer operation), which is equivalent to 1,371 cycles of 1,200 kWh.

6.1.2 HESS Power Split

The use of a hybrid storage requires a strategy for sharing the power between the High-Energy (HE) -ESS (referred here as the BESS subsystem) and the High-Power (HP) -ESS subsystems. The method used in this work is based on low pass filtering of the load power demand. The advantage of the proposed method is that it can easily be implemented in a real power management system. However, the method does not guarantee that the true optimal power split is found.

Fig. 6.4 illustrates the core power split strategy based on low pass filtering used to determine the share of the load/HESS power (P_{HESS}) that is routed to and from the HE-ESS and HP-ESS subsystems. The power split strategy can be defined by three main parameters: the low pass filter cut-off frequency (F_0), the maximum discharge power of HE battery ($P_{HE.DCHmx}$) and the maximum charge power of HE battery ($P_{HE.CHmx}$). Also, the strategy considers an additional constraint to avoid the power flow between ESS sub-systems, so it is always checked that:

$$P_{HESS}(t) = P_{HE}(t) + P_{HP}(t) \quad | \quad \begin{cases} P_{HE}(t) \geq 0 \;\&\; P_{HP}(t) \geq 0 & \forall\, P_{HESS}(t) \geq 0 \\ P_{HE}(t) \leq 0 \;\&\; P_{HP}(t) \leq 0 & \forall\, P_{HESS}(t) < 0 \end{cases}$$

where, $P_{HESS}(t)$ is the HESS power time series, $P_{HE}(t)$ is the power time series split to HE battery sub-system and $P_{HP}(t)$ is the power time series split to HP-ESS sub-system.

Fig. 6.5 shows examples of the power time series obtained by the power split algorithm when using different parameters. The cycled energy associated with the resulting power time series is also plotted.

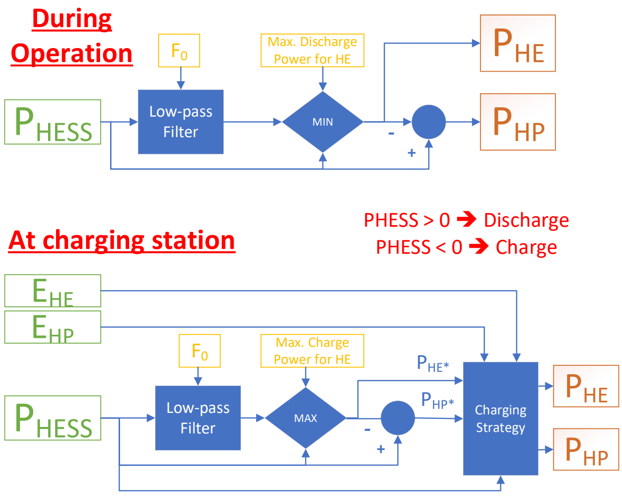
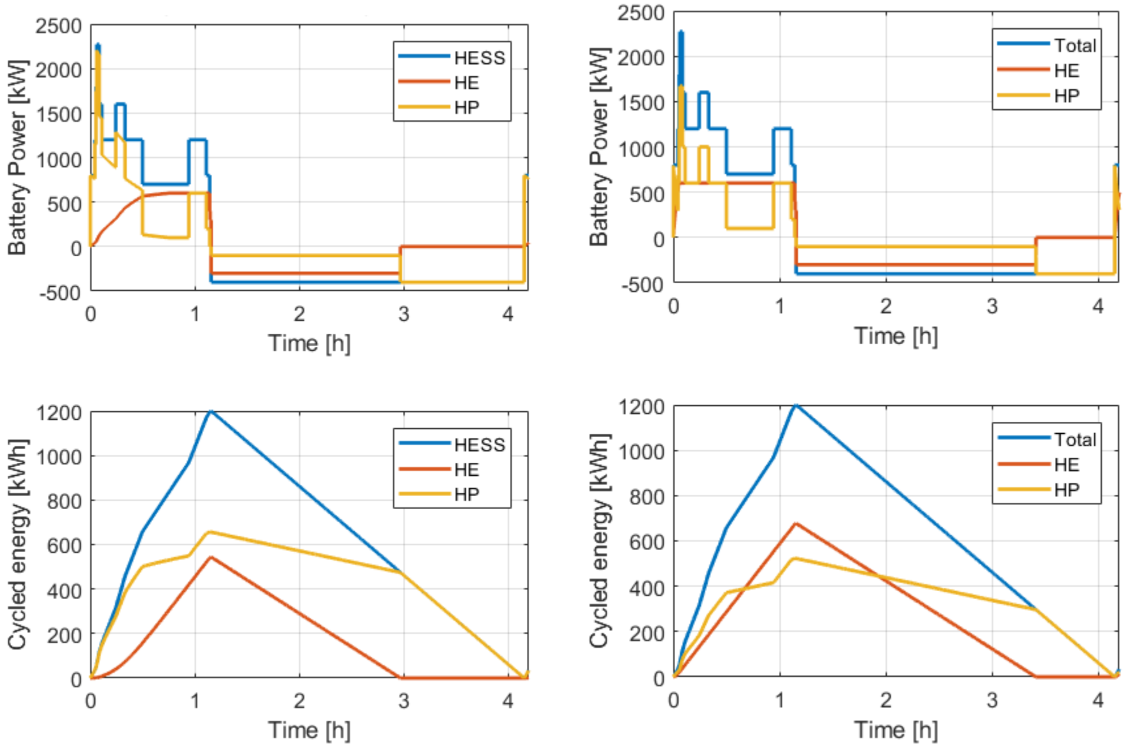
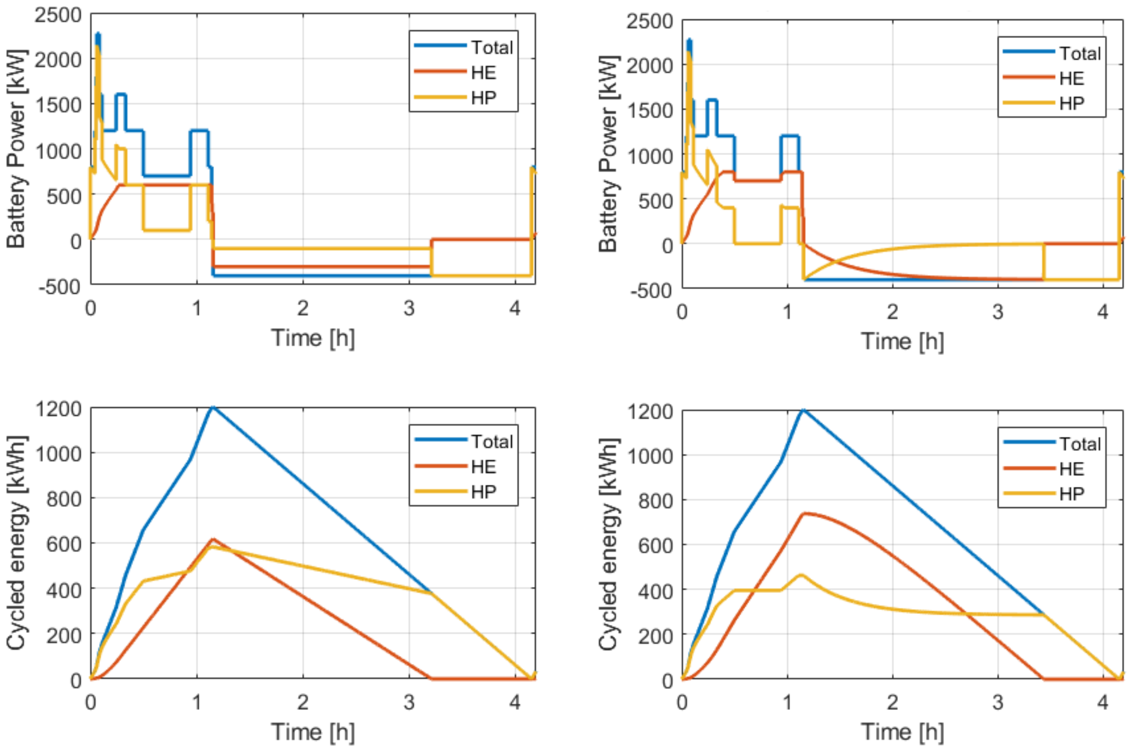


FIG. 6.4: POWER SPLIT STRATEGY BASED ON LOW PASS FILTERING FOR ZERO-EMISSION VESSELS. (TOP: STRATEGY DURING HESS DISCHARGING; BOTTOM: STRATEGY DURING HESS CHARGE OPERATION AT CHARGING STATION)


Battery Power [kW]
Time [h]
HESS
HE
HP
Total
Cycled energy [kWh]

a) b)



c) d)

FIG. 6.5: EXAMPLE OF TIME SERIES OBTAINED BY THE POWER SPLIT ALGORITHM WITH A) F_0=50MHZ, $P_{HE.DCHmx} = 600kW, P_{HE.CHmx} = 300kW$; B) F_0= 1000MHZ, $P_{HE.DCHmx} = 600kW, P_{HE.CHmx} = 300kW$; C) F_0= 100MHZ, $P_{HE.DCHmx} = 600kW, P_{HE.CHmx} = 300kW$; AND D) F_0= 100MHZ, $P_{HE.DCHmx} = 800kW$, $P_{HE.CHmx} = 400kW$;

The power split algorithm is shown in Fig. 6.6. The power split core strategy, shown in Fig. 6.4, is used within in the block called HE-HP power split in the power split algorithm. The process is done for all the time series composing the power profile.

The power split method has three parameters, however, only two of these parameters (F_0 and $P_{HE.DCHmx}$) have been considered as free design parameters to guaranty the energy balance of the resulting power time series, then $P_{HE.CHmx}$ has been set as the maximum charge power of the time series and then recalculated based on the energy used and available charging time as output of this stage.

Different combinations of F_0 and $P_{HE.DCHmx}$ are explored in the optimization, implying also that the filter parameters used for one of the time series within the given power profile can be different from the filter

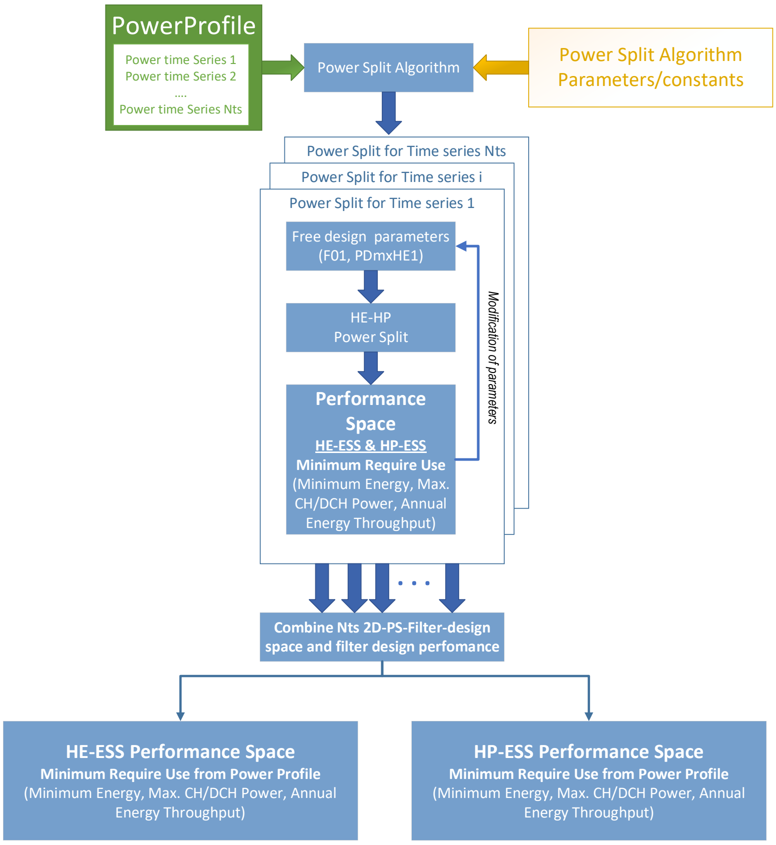


FIG 6.6: POWER SPLIT ALGORITHM

parameters used for the other time series of the given power profile. This implies that for each application power profile (composed by $\boldsymbol{N_{ts}}$ power time series) the power split design space has $2xN_{ts}$ free design parameters (two filter parameters per each time series).

For example, a design space defined by 20 different values of F_0, from zero (associated with monotype HP-ESS) to infinite (associated with monotype HE battery systems), and 10 different values for $P_{HE.DCHmx}$, from 10% to 100% of the maximum P_{HESS}, has been considered for the HESS design approach for each power profile. Associate with the defined design space, a total of $200^{N_{ts}}$ possible power split combinations have been explored and mapped to the output performance space in this step (e.g., for a power profile with 2 time series then 40,000 possible power split combinations are explored).

Two performance spaces are obtained in this step, associated to each ESS sub-system. Each performance space is defined by four specific requirements, calculated from the power time series split to each ESS sub-system:

- **The minimum usable energy of the ESS sub-system ($\boldsymbol{E_{MRU}}$)**: it is the minimum energy capacity that need to remain at the end of design life. It is possible to estimate a required energy for each power time series associated to a battery sub-system by the difference between maximum and minimum change in stored energy, which is calculated by the integration of the power time series, e.g., the required energy (E_{reqHE}) by a power time series $P_{HE}(t)$ split to the HE battery can be estimated by:

$$E_{reqHE} = \max\left(\int P_{HE}(t) \cdot dt\right) - \min\left(\int P_{HE}(t) \cdot dt\right)$$

  Then, the minimum required usable energy (E_{MRU}) of the battery sub-system is equal to the maximum required energy from all N_{ts} power time series of the power profile:

$$E_{MRU} = \max(E_{req1}, E_{req2}, \dots, E_{reqNts})$$

- **The required maximum continuous & peak charge power ($\boldsymbol{P_{MCC}}$ & $\boldsymbol{P_{MPC}}$)**: It is possible to estimate a minimum required charge power associated to each power time series by taking the maximum between the required energy per cycle and the available charging time per cycle (assuming energy balance per cycle). Then, the required maximum continuous charge power is calculated as the maximum value along all the required charge power associated to the N_{ts} power time series of the power profile.
- **The required maximum continuous & peak discharge power ($\boldsymbol{P_{MCD}}$ & $\boldsymbol{P_{MPD}}$)**: This is estimated from the maximum value of all maximum discharge power associated to all N_{ts} power time series of the power profile.
- **The annual energy throughput (*AET*)**: The energy throughput associated to each power time series can be found by integrating either charge power or discharge power, or simply approximated by integrating the unsigned power and divide by 2; e.g., the annual energy throughput ($AET_{HE,i}$) associated to the power time series $P_{HE,i}(t)$ split to the HE battery can be estimated by:

$$AET_{HE,i} = \int_{t=0}^{t=1year} \frac{|P_{HE,i}(t)|}{2} \cdot dt$$

  Then, the annual energy throughput associated to a given power profile is calculated by adding the energy throughput associated to each power time series composing the power profile, e.g., for the HE battery sub-system:

$$AET_{HE} = \sum_{i=1}^{N_{ts}} AET_{HE,i}$$

6.1.3 ESS Sizing algorithm

Fig. 6.7 illustrates the different factors to consider guarantying enough remain battery capacity at the end of design life (E_{EDL}). The ESS sizing algorithm estimates the minimum capacity to be installed considering the following criteria:

- to charge and discharge the **minimum usable energy** prescribed by the load profile to the end of design life (EDL) and maintaining the State of Charge within the defined minimum (SOC_{mn}) and maximum (SOC_{mx}) set design limits (e.g. between 10% and 90%):

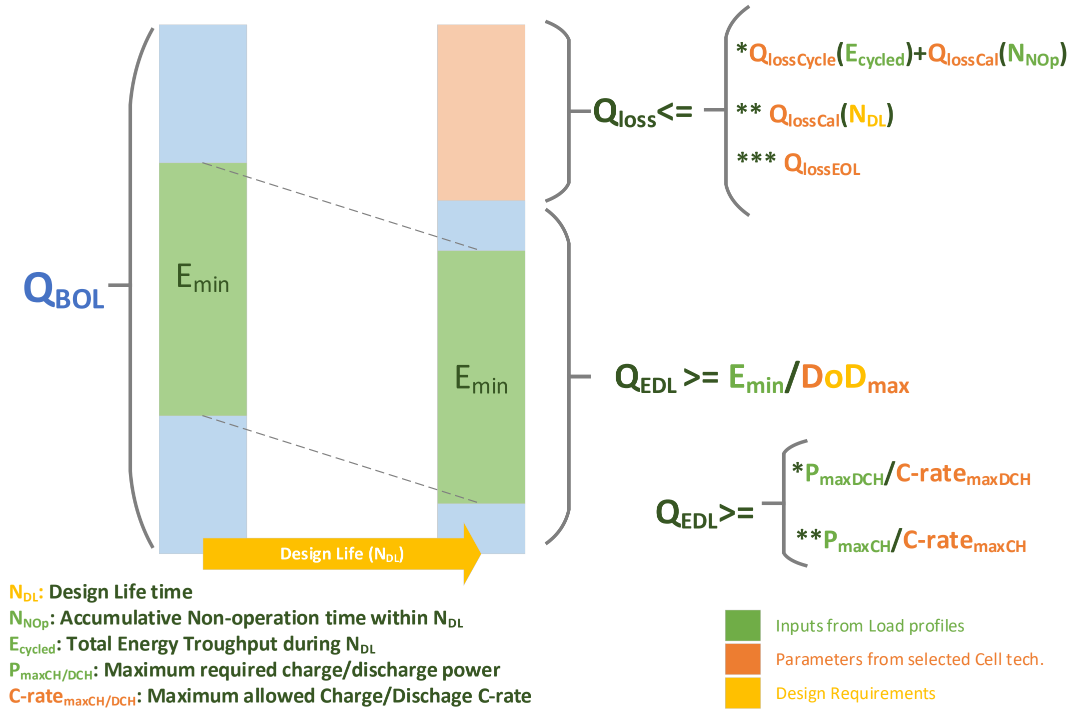


Fig. 6-7: Illustration of ESS sizing criteria

$$E_{EDL} \geq \frac{E_{MRU}}{SOC_{mx} - SOC_{mn}}$$

- to allow a charging power at least as large as the required maximum continuous/peak charging power in the defined load profile:

$$E_{EDL} \geq \frac{P_{MCC}}{C_{rate,MCC}} \;\; \& \;\; E_{EDL} \geq \frac{P_{MPC}}{C_{rate,MPC}}$$

- to allow a discharging power at least as large as the required maximum discharging power in the defined load profile:

$$E_{EDL} \geq \frac{P_{MCD}}{C_{rate,MCD}} \;\& \; E_{EDL} \geq \frac{P_{MPD}}{C_{rate,MPD}}$$

- to allow the energy cycling prescribed by the input load profile without causing battery cells to reach their end of life (EOL) before end of design life:

$$E_{EDL} \geq E_{EOL}$$

- to ensure that calendar capacity degradation alone will not reduce the storage capacity, before end of design life, to such extend that State of Charge goes outside the set design limits for the defined load profile:

$$E_{BOL} - E_{EDL} \leq Q_{Cal}(N_{DL})$$

- to ensure that cycling capacity degradation, in combination with calendar capacity degradation in non-used periods, will not reduce the remaining capacity at end of life, to such extend that State of Charge goes outside the set design limits for the defined load profile:

$$E_{BOL} - E_{EDL} \leq Q_{Cal} + Q_{Cycle}$$

Each of the previously mentioned criteria gives a minimum required capacity to be installed (E_{BOL}), so this implies that the minimum capacity to install is given by the maximum along all calculated energy capacities.

The aging process in battery cells is reflected mainly in capacity loss and increment of internal resistance. In this work, it has been considered the capacity degradation as the main end of life (EOL) criterion. Thus, the EOL criterion (k_{EOL}) for the ESS has been related to the capacity fade of battery cells (Barrera-Cardenas, Mo, & Guidi, 2019):

$$k_{EOL} = \left(1 - \frac{E_{EOL}}{E_{BOL}}\right) \cdot 100\%$$

where E_{BOL} is the ESS total energy capacity at beginning of life (BOL) and E_{EOL} is the remaining ESS capacity at end of life. Then, $k_{EOL} = 20\%$ for the considered battery technology.

The estimation of the fractional capacity degradation (capacity fades in a period with defined conditions) depends on whether the ESS is in operation (charging/discharging) or not. When the ESS is not in operation, the phenomenon is known as calendar degradation (aging during storage). On the other hand, if the ESS is in operation, then a cycling degradation will occur (Barrera-Cardenas, Mo, & Guidi, 2019).

A very simple degradation model is used in this algorithm. It is certainly possible to use more sophisticated. However, it is typically difficult to get access to the necessary data, even for the simple model used here. More sophisticated models will require more parameters for the cell degradation that will be even harder to get hold on. The following assumptions have been considered:

- As the end-of-life criteria has been linked to the capacity fade, then the considered degradation model only considers the effects on capacity fade given by calendar aging and cycling degradation.
- It is assumed that calendar aging is a linear process, reducing the capacity with an amount equal to a fixed percentage of the initial capacity whenever the battery is not in use. A battery with 1% calendar aging per year will then have 90% of its initial capacity after 10 years and 80% after 20 years.
- Calendar aging is assumed to apply whenever the battery is not cycled, that is, when the load profile has periods of zero power flow. It is assumed that the cycle degradation also includes the calendar degradation in those intervals power is flowing.
- It is assumed that superposition applies such that the incremental effect of each cycle can be added, and such that incremental calendar capacity loss can be added to the capacity loss due to the cycles. This

means that it is assumed that the capacity loss is the same independent of the sequence of cycles and periods with no use of battery (calendar aging).

- It is assumed that cycling degradation is linearly proportional to the energy throughput. The proportionality factor is estimated based on the number of equivalent full cycles to the end-of-life, neglecting the non-linear effects of different depth-of-discharge on the actual cycling degradation. So, a cycle that goes from 80% SoC to 40% SoC and back to 80% has a DoD of 40%. This will correspond to 40/100=0.4 equivalent full cycles.

Based on the previous assumptions, the total degradation (ΔQ_{EDL}) at the end of design life (EDL) is estimated by:

$$\frac{Q_{lossEDL}}{E_{BOL}} = \Delta Q_{EDL} = \Delta Q_{cal} + \Delta Q_{cycle}$$

where ΔQ_{cal} is the total calendar degradation and ΔQ_{cycle} is the total cycling degradation at the EDL. The calendar degradation can be estimated by:

$$\Delta Q_{cal} = \frac{Q_{LossCal}}{100} \cdot (365 - ADY) \cdot T_{EDL}$$

where $Q_{LossCal}$ is the capacity loss per year due to calendar aging (in percent of initial capacity), *ADY* is the expected operating days per year, and T_{EDL} is the design lifetime in years.

On the other hand, the capacity loss (in kWh) associated to cycling degradation can estimated by:

$$\Delta Q_{cycle} = \frac{(100 - k_{EOL})}{DoD_{ref} \cdot N_{cycleREF}} \cdot AET \cdot T_{EDL}$$

where $N_{cycleREF}$ is the reference number of cycles to reach EOL criteria (k_{EOL}) with reference depth of discharge (DOD_{ref}) and *AET* is the expected annual energy throughput in kWh.

6.1.4 HESS first screening

Each potential solution from power splitting algorithm has different requirements affecting the sizing of individual HE- and HP-ESSs. The potential HESS solutions are compared against monotype solutions (ESS based on only one technology, NMC battery) in terms of required installed capacity and potential capital cost reduction from core cells. The HESS first screening adopts a graphical approach for easy comparison, where the potential HESS solutions are represented by plotting the required installed capacity of each subsystem (BESS and HP-ESS). Fig. 6.8 shows the methodology summary for HESS first screening graphical representation.

The HESS installed capacity (Q_{HESS}) is estimated by the sum of installed energy capacity of HE-ESS or BESS (Q_{HE} or (Q_{BESS})) and the installed energy capacity of HP-ESS (Q_{HP}):

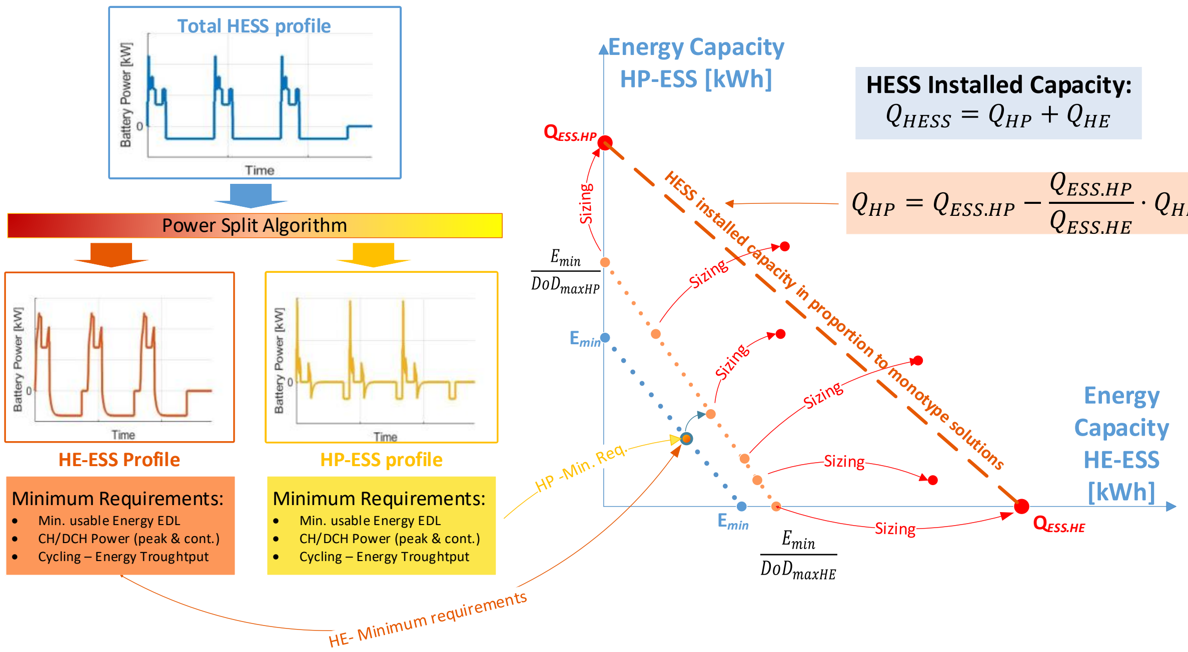


Fig. 6.8: Methodology summary for HESS first screening graphical representation

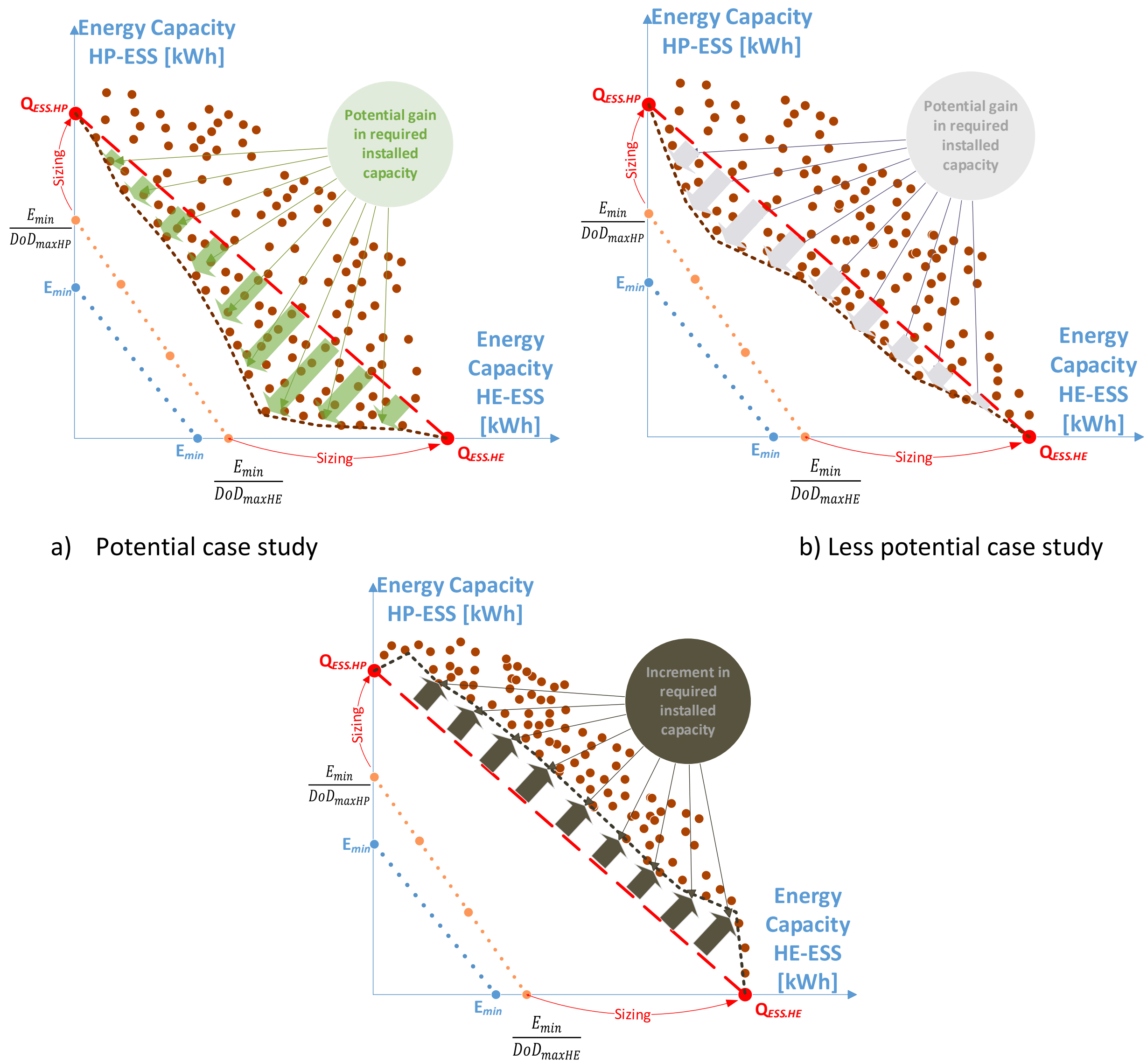
$$Q_{HESS} = Q_{HE} + Q_{HP}$$

Within the potential solutions, there are two solutions of interest, the monotype solutions, which are solutions based on only one type of technology, either HE-ESS (like NMC battery) or HP-ESS (like SC or SMES). The HESS solution space can be compared against a reference line representing the HESS installed capacity in proportion to installed capacity of monotype solutions, so a potential gain in required installed capacity can be found if there are solutions which fulfil the following criteria:

$$Q_{HP} < Q_{ESS.HP} - \frac{Q_{ESS.HP}}{Q_{ESS.HE}} \cdot Q_{HE}$$

where, $Q_{ESS.HP}$ is the required installed capacity of monotype HP-ESS solution, and $Q_{ESS.HE}$ is the required installed capacity of monotype HE-ESS (or BESS) solution. Accounting for this criterion, a potential case study can be graphically detected based on gains in required installed energy for HESS.

Fig. 6.9 shows example of graphical representation of potential case studies based on gains in required installed energy for HESS. Fig. 6.9-a and Fig. 6.9-b show potential case studies, so there are HESS solutions which fulfil the previous presented criterion. However, Fig. 6.9-b, compared with Fig. 6.9-a, shows a less potential case study, mainly because less amount of solutions fulfil the potential gain in required installed capacity criterion but also because the HESS solutions are characterized by the higher required installed capacity of HP-ESS compared to HE-ESS capacity, which could be more challenging in term of cost as the



a) Potential case study

b) Less potential case study

c) Not potential case study

FIG. 6.9: EXAMPLE OF GRAPHICAL REPRESENTATION OF POTENTIAL CASE STUDIES BASED ON GAINS IN REQUIRED

HP-ESS has normally a higher cost per unit energy than HE-ESS technology. Therefore, HESS solutions with $Q_{HE} >> Q_{HP}$ will have more potential benefits. On the other hand, Fig. 6.9-c shows a case when the analysed HESS profile does not represent a potential case of study as there are not HESS solution which fulfil the potential gain in required installed capacity criterion.

On the other hand, an additional criterion can be considered by checking if there are HESS solutions with a potential reduction in capital cost of the HESS compared with a monotype BESS. As a first approach, it is proposed to account only for the capital cost related to ESS cell cost, as it normally counts for around 70-80% of total ESS cost. The total cell cost of a HESS solution can be expressed by:

$$Cost_{HESS} = Cost_{HE} \cdot Q_{HE} + Cost_{HP} \cdot Q_{HP}$$

where $Cost_{HE}$ and $Cost_{HP}$ are the cost per unit energy of HE-ESS and HP-ESS cells, respectively. Taking as baseline the cost of a monotype HE-ESS solution, then a potential reduction of HESS solutions against monotype solution can be estimated by checking that the total HESS cell cost is minor than the monotype HE-ESS cell cost, that is finding solutions fulfilling the following criterion:

$$Q_{HP} < \frac{Cost_{HE}}{cost_{HP}} \cdot (Q_{ESS.HE} - Q_{HE})$$

Fig. 6.10 shows an example of a HESS power profile with some HESS solutions showing potential reduction in capital cell cost. It should be mentioned that even though there is not a potential reduction in HESS cell cost still it could be a potential reduction in total HESS cost coming from other potential benefits do not consider in this first assessment.

6.2 Analysed marine profile cases

Table 6.1 summarizes the analysed marine application profiles within this work along this the characteristic of the power time series and electric system configuration. The marine application profile data from three different sources have been considered: three profiles are from log data of relevant vessels provided by Vard, seven profiles are from relevant power profile data reported in (SEABAT, 2021), and three profiles are from simulations of specific vessel applications/operations provided by Sintef Ocean in combination with log data of relevant vessels provided by Vard.

TABLE 6.1 ANALYSED MARINE PROFILES AND DATA.

CASE/VESSEL TYPE	SOURCE	SAMPLE TIME	DATA LENGTH	CHARACTERISTICS

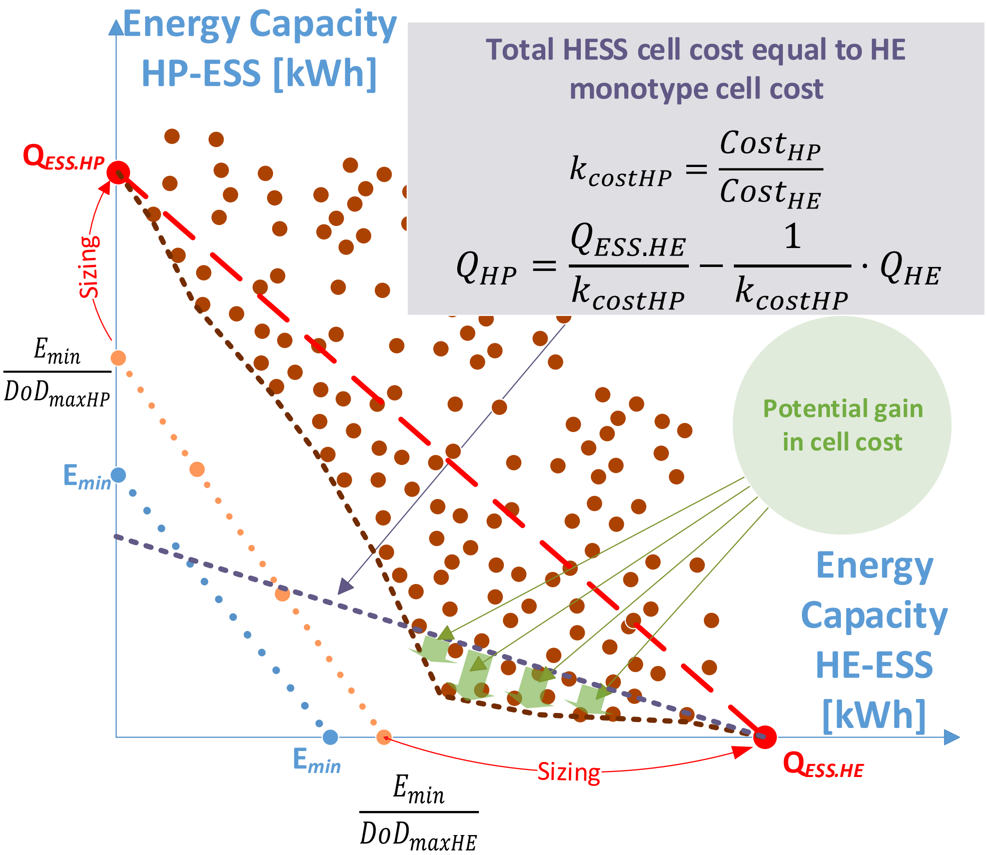


FIG. 6.10: EXAMPLE OF A HESS POWER PROFILE WITH SOME HESS SOLUTIONS SHOWING POTENTIAL REDUCTION IN CAPITAL COST.

Ferry	Log data provided by Vard	6s	2 hours	Full electric, two charging stations, 32 trips per day
Platform Supply Vessel (PSV)		15s	13 days	4xDGs + ESS,
Trawler		15s	2 days	Hybrid. Power from shaft generator.
Ro-Ro Ferry 1	Literature SEABAT project [35]	1s	1 day	Full electric, two profiles with seasonal variation
Ro-Ro Ferry 2		30s	1 day	Full electric, two profiles by including a case when one of the charging stations is not available.
Harbour Tug		30s	8 hours	Full electric. Standard vs. heavy job day
Urban Ferry		30s	2 days	Full electric. Short vs. Long trip
Water Bus		30s	1 day	Full electric. Short vs. Long trip
Fish Carrier		30s	1 day	Hybrid. Peak Shaving + Spinning Reserve
Fishing Vessel		30s	1 day	Hybrid. Peak shaving + Boost function
Bulk carrier + Crane operation at port	Simulations provided by Sintef Ocean	1s	15.5 hours	Hybrid. Crane op. + spinning reserve
Dynamic Position Vessels + crane operation		1 s	13 days	Hybrid. PSV log data + simulation
OSV + heave compensation system		1 s	13 days	Hybrid. PSV log data + simulation

Table 6.2 shows the ESS reference cell technology and main parameters considered within the HESS first screening evaluation. The 94Ah NMC Li-ion cell from Samsung has been considered as reference battery technology, and the SCA3200 supercapacitor cell from Skeleton has been considered as reference supercapacitor technology. On the other hand, the SMES 750 kJ, 200kW-2.5s from ASG Superconductors has been considered as reference SMES system. About the reference ESS cost per unit energy, it can be mentioned that the SC-ESS cost per Wh is 12 times higher than the NMC battery cost and the SMES cost per Wh is 340 times higher than the NMC battery cost. Further cost analysis for SC and SMES can provide possible further reductions.

For the HESS first screening, the reference ESS parameters for battery and SC have been estimated based on available core cell parameters, however they may be replaced by system level parameters in the future analysis.

TABLE 6.2: ESS REFERENCE TECHNOLOGY AND MAIN PARAMETERS

	BATTERY - NMC	**SUPERCAP.**	**SMES**
Ref. cell	94AH-NMC @Samsung	SCA3200 @Skeleton	750 kJ, 200kW-2.5s @ ASG Superconductors
Capacity	94Ah – 345 Wh	1.69 Ah- 3.61 Wh	0.278 Ah – 208 Wh
Voltage	3.68V {2.7, 4.15}	2.14V {1.42, 2.85}	750 V
Discharge Current	**150 A cont. (1.6C)** **409 A Peak (4.3C)**	**273 A cont. (161C)** **2890 A Peak (1710C)**	**88.9 A cont. (320C)** **1000 A Peak (3600C)**
Charge Current	**72 A cont. (0.8C)** **270 A Peak (2.9C)**	**273 A cont. (161C)** **2890 A Peak (1710C)**	**88.9 A cont. (320C)** **1000 A Peak (3600C)**
Usable SoC	80%	75% (50% Vrated)	66.7% (500/750)
Cell Cost	**0.42 EUR/Wh**	**5 EUR/Wh**	**144 EUR/Wh**
Calendar Life @EOL (20% Qloss)	**17 years**	**10 years**	**∞**
Cycle life @EOL (20% Qloss)	4255 full cycles @0.5C/1C	1.000.000 (75% DoD) @1C/1C	**∞**

The ESS EoL criterion has been based on system capacity loss, and a fix value of 20% capacity loss has been considered for NMC and SC technologies. SMES is characterized by a very low or not degradation regarding capacity loss, so the SMES capacity fade has been neglected.

A current safety margin of 50% for the peak current and 20% for the continuous current from the values reported in Table 10.2 have been considered for estimation of the C-rates at system level.

For all the analysed cases, a ship lifetime of 30 years has been considered, and unless otherwise specified the following design life for the ESS applies:

- SC Design life minor or equal to 7.5 years (equivalent to at least 4 replacements during the ship lifetime)
- NMC Design life minor or equal to 15 years (equivalent to at least 2 replacements during the ship lifetime)
- SMES Design life equal to the Ship lifetime.

On the other hand, for the case of HESS based on combination of SMES & Batteries, additional assumptions have been considered:

- Assuming liquid hydrogen as fuel (combustion or FC) for vessels.
- SMES cooling system by integration with hydrogen storage onboard, so weight and cost savings by cooling system integration.
- HESS design life to match with Vessel lifetime, and assuming replacement of batteries every 10 years.

6.3 Selected case studies

Table 6.3 shows the summary of results for analysed cases and potential for HESS implementation when NMC batteries and SC are considered. On the other hand, Table 6.4 shows the summary of results for analysed cases and potential for HESS implementation when NMC batteries and SMES are considered. The

TABLE 6.3: SUMMARY OF RESULTS FOR ANALYSED CASES AND POTENTIAL FOR HESS IMPLEMENTATION WHEN NMC BATTERIES AND SC ARE CONSIDERED.

CASE/VESSEL TYPE	SOURCE	POTENTIAL CASE STUDY	REMARKS	FOR MORE INFO.
Ferry	Log data provided by Vard	OK	Full Electric. Potential cell cost.	VARD
Platform Supply Vessel (PSV)		NO -> TBD	EMS-ship level to be analysed.	VARD
Trawler		OK	EMS-ship level to be analysed. Low margin.	VARD
Road Ferry 1&2	Literature SEABAT project public deliverable D2.1	OK	Full Electric. High potential gain in cell cost.	RINA
Harbour Tug		OK - TBD	Full Electric. No cost margin and low margin in Capacity.	RINA
Urban Ferry		NO	Full Electric. No margin.	--
Water Bus		OK	Full Electric. Low margin.	--
Fish Carrier		OK	Hybrid. High potential gain in cell cost.	RINA
Fishing Vessel		OK	Hybrid. No margin in cost and low margin in Capacity.	VARD - RINA
Bulk carrier - Crane op. at port		OK	Further analysis for different genset levelling values	RINA
DP & crane operation	Simulations provided by Sintef Ocean	NO	Crane power negligible compared to other loads.	VARD
OSV - AHC		OK -TBD	SC seems optimal solution. SC already in plan for OSV.	VARD

results have been presented and discussed in a Workshop for the finalisation of the case studies.

TABLE 6.4: SUMMARY OF RESULTS FOR ANALYSED CASES AND POTENTIAL FOR HESS IMPLEMENTATION WHEN NMC BATTERIES AND SMES ARE CONSIDERED.

CASE/VESSEL TYPE	SOURCE	POTENTIAL CASE STUDY	REMARKS
Ferry	Log data provided by Vard	OK	Full Electric. Potential cell Cost ratio < 20
Platform Supply Vessel (PSV)		NO - TBD	EMS-ship level to be analysed.
Road Ferry	Literature SEABAT project public deliverable D2.1	OK	Full Electric. Relatively good margin in capacity.
Urban Ferry		NO	Full Electric. No margin.
Water Bus		OK	Full Electric. No cost margin and low margin in Capacity.
Fish Carrier		OK	Hybrid. Relatively good margin.
DP + crane operation	Simulations provided by Sintef Ocean	NO	Crane power negligible compared to other loads.
OSV - AHC		OK - TBD	Good case when battery design life 10

The initial analysis pointed out that several case studies could be suitable for the V-ACCESS project. First, the ferry will be included in further studies as it is the only case where propulsion is fully electric, and the consortium have log data for this vessel.

Then it was discussed the viability of the bulk carrier. It was discussed that a container ship would have significantly higher power peaks than a bulk carrier. However, a container ship was not included in the cases where data were available, and it would be difficult to proceed with this case. For this reason, preference was made to the vessels for which log-data are available and can be provided internally in the consortium.

It was also discussed the potential case of Cruise vessels. It emerged that this case does not currently have sufficient information to proceed with further studies, and it was not included in the final list.

The use cases have been selected and ranked in the following order:

1. **Electric ferry** – power profile will be provided by log data and the case described in section 9 and the appendix. This case will be based on the marine application case described in the appendix. It will be checked if additional log data is available for accounting possible seasonal power profile variations.
2. **Fish carrier** – power profile data will be provided by simulations. The target vessel is a fish carrier with overall length of 86 m and breadth of 18 m. The maximum speed and cruising speed are around 11.4 knots and 10.9 knots, respectively. The propulsion power at maximum and cruiser speed are 2,700 kW and 1,300 kW, respectively.

3. **Bulk carrier / Container ship** – for the power profile data, it has been proposed to use the crane operation of bulk carrier as the case study. As for the vessel information, the target vessel type is a 50,000-dwt open-hatch dry bulk carrier.
4. **OSV – AHC** – Typical OSV power load data provided by log data based on PSV case described in section 9 and in the appendix; and in combination with AHC simulations.
5. **Trawler** – power profiled data provided by log data. This case will be based on the marine application case described in section 9 and in the appendix.
6. **Harbour Tug** – Power profile data will be provided by simulations. The target vessel is a harbour tug with overall length of 32 m and breadth of 12 m. The maximum speed and cruising speed are around 14 knots and 7 knots, respectively. The propulsion power at maximum and cruiser speed are 1,800 kW and 500 kW, respectively.

7 Conclusions

This document has reported on the activities of Task 1.1 & 1.2 for work package 1 (WP1) of the V-Access project. It has mainly reviewed energy storage technologies and compared them for applications onboard marine vessels and provided examples of electric and hybrid electric vessels that can be suitable for these technologies. The state-of-the-art lithium-ion batteries were first covered and compared qualitatively and quantitively, and then compared with other short-term energy storage systems, specifically ultracapacitors/supercapacitors and superconductive magnetic energy storage systems, based on their properties, cost, and other key performance indicators. It can be concluded that ultracapacitors and superconductive magnetic energy storage systems are only capable of providing very high-specific power in comparison with lithium-ion batteries, whilst their utilisation for onboard bulk energy storage is still restricted due to their low specific energy. Therefore, the study has evidenced that their utilisation for electric and hybrid vessels is optimised when used in combination with batteries to provide peak or dynamic load power, whilst minimising the battery pack power to its average level. As such, combined/hybrid energy storage system onboard can result in extending the service life of the battery packs, thereby reducing replacement costs. Currently, both ultracapacitors and superconductive magnetic energy storage systems are suitable to play this role within the onboard power system.

The vessels selected as potential use cases are described in detail in this report, including their specifications and main purpose of utilisation. The cases have been studied from a point of view of optimisation of the battery usage and minimisation of the total installed capacity and they have been ranked in terms of the potential reduction of the same compared to the case where only batteries are used. The seven selected cases are the electric ferry, the fish carrier, bulk carrier / container ship, offshore supply vessel with active heave compensator, the trawler, and the harbour tug.

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9 Appendix A

9.1 Description of lithium-ion chemistries

a. Lithium Cobalt Oxide (LCO)

LCO is a common lithium-ion chemistry used in electric vessels due to its high energy density, which makes it a good choice for applications that require a considerable stored energy in a small space. They are also relatively environmentally friendly, with no emissions or hazardous waste produced during operation. However, LCO batteries are relatively expensive, and they are sensitive to high temperatures, which can reduce their performance and lifespan. Additionally, LCO batteries have a high risk of thermal runaway, which can lead to safety issues.

b. Lithium Manganese Oxide (LMO)

LMO is another common lithium-ion chemistry used in electric vessels due to its good balance between high energy density and high-power density. They have a long cycle life and are relatively safe, with a low risk of thermal runaway. LMO batteries are also environmentally friendly, with no emissions or hazardous waste produced during operation. However, LMO batteries have a lower energy density compared to other lithium-ion chemistries, which means they may require more space to store the same amount of energy. They also have moderate power output compared to other chemistries, which may not be suitable for applications that require very high-power output over a short period of time.

c. Lithium Nickel Cobalt Aluminium Oxide (NCA)

NCA is another lithium-ion chemistry which offers a very high energy density, making it a good choice for electric vessels that require a high power in a small space. They have a relatively long cycle life and are relatively safe if properly managed and monitored. NCA batteries also have a high-power output, making them suitable for applications that require high power output over a short period of time. However, NCA batteries are relatively expensive, and they are sensitive to high temperatures, which can reduce their performance and lifespan. Additionally, NCA batteries have a high risk of thermal runaway, which can lead to safety issues.

d. Lithium Nickel Manganese Cobalt Oxide (NMC)

NMC is a lithium-ion chemistry that offers a good balance between high energy density and high-power density, making it a good choice for electric vessels that require both. They have a relatively long cycle life and are relatively safe, with a low risk of thermal runaway. NMC batteries are also relatively inexpensive compared to other lithium-ion chemistries. However, NMC batteries have a lower energy density compared to Lithium Nickel Cobalt Aluminium Oxide (NCA), which means they may require more space to store the same amount of energy. They also have a lower power output compared to NCA, which may not be suitable for applications that require very high-power output over a short period of time.

e. Lithium Iron Phosphate (LFP)

LFP is a lithium-ion chemistry which can offer a high level of safety and stability, making it a good choice for electric vessels that require a reliable and safe energy source. LFP batteries have a long cycle life and are relatively inexpensive compared to other lithium-ion chemistries. They are also environmentally friendly, with no emissions or hazardous waste produced during operation. However, LFP batteries have a lower energy density compared to other lithium-ion chemistries, which means they may require more space to store the same amount of energy. But they have a higher power output compared to other chemistries, which may not be suitable for applications that require very high-power output over a short period of time.

f. Lithium Titanate (LTO) Batteries

LTO batteries have a very high-power output and a long cycle life. They are also more stable than other lithium-ion batteries and are less prone to thermal runaway. LTO batteries are made up of lithium titanate, which allows for a balance of power and stability. They are also more resistant to charging and discharging cycles than other lithium-ion batteries, which makes them a popular choice for applications that require frequent charging and discharging. However, LTO batteries have a lower energy density than other lithium-ion batteries, which can limit their range. They are also more expensive to manufacture than other lithium-ion batteries.

9.2 Quantitative comparison of Li-ion batteries with different chemistries

Most reported data in the literature about Li-ion batteries vary widely with relevance to each Li-ion chemistry, including their characteristics and performance. The following table provides data for five types of Li-ion batteries based on different chemistries, which can be useful for a quantitative comparison [1-3].

TABLE 9.1: QUANTITATIVE COMPARISON OF DIFFERENT LI-ION BATTERY TECHNOLOGIES FOR USE IN ELECTRIC VESSELS

BESS type Features	LFP	LTO	NCA	NMC	LMO
Specific energy [Wh/kg]	90 – 120	50–80	200-265	150 – 220	100 – 150
Nominal cell voltage [V]	3.25V	2.4V	3.6V	3.6V	3.7V
Charging rate, C (W/Wh)	1 C	1 - 5 C	0.7 C	0.7 - 1 C	0.7 - 1 C
Discharging rate, C (W/Wh)	1 - 25 C	10 - 30 C	1 C	1 - 2 C	1 - 10 C

Charging/discharging cycles	2,000	3,000 - 7,000	500	1,000 – 2,000	300 – 700
Temperature for thermal runaway	270°C	N/A	150°C	210°C	250°C
Cost: USD / kWh	580	1,005	350	420	N/A

9.3 Description of power electronics converters used for energy storage

a. Buck Converters

The buck converter is a topology which consists of a single power switch that is arranged in a boost configuration with an interfacing filter. The buck converter can only decrease the voltage of the ultracapacitors, and when bidirectional design is implemented, it can regulate the power flow in both directions (to and from the energy storage).

b. Boost Converters

The boost converter is a topology with single power switch which is arranged in boost configuration with an interfacing inductance. The boost converter can only increase (boost) the voltage of the energy storage, and it can regulate the power flow in both direction when bidirectional design is employed.

c. Buck-Boost Converters

The buck-boost converter is a combination of two power switches that are arranged in buck-boost configuration with the connecting inductance. The buck-boost converter can either increase (boost) or reduce (buck) the voltage of the ultracapacitors whilst regulating the power flow in both directions, or when charging and discharging the ultracapacitor.

d. Dual Active Bridge Converters

The dual active bridge (DAB) converter is a topology that can also be used for UCES systems. It consists of two full-bridge converters that are connected in series through a high-frequency transformer for galvanic insulation between the converters' sides. This type of isolated converters is used for specific grounding schemes where some parts of the installation need to be kept electrically floating for reasons of electromagnetic noise/compatibility.

9.4 Reference data used to evaluate the main characteristics of UCES and SMES

Table 9.2 shows the characteristics and specifications of Skeleton ultra-capacitor 51V177F module [39].

Table 9.2: The characteristics and ratings of the Skeleton ultra-capacitor 51V177F module [39]

Characteristics	Skeleton ultra-capacitor 51V177F module
Rated Voltage (V)	51
Rated Capacitance (F)	177
Equivalent resistance (ESR) (mΩ)	4.0 (DC 1s)
Rated max peak current for 1 s (kA)	2.64
Max Stored Energy (Wh)	63.9
Specific Energy (Wh/kg)	4.0 – 16 (for graphene based)
Specific power (kW/kg)	10.2 (calculated from 1s ESR)
Energy Density (Wh/L)	4.7
Power Density (kW/L)	12.0 (calculated from 1s ESR)
Expected weight of the module in kg	16
Expected volume of the module in L	13.5
Length x width x height (mm)	422 x 194 x 198
Working temperature (range)	-40 to +65 °C
Lifetime (hours)	1,500 (@ 51 V and max operating temperature) 2,500 (@ 48 V and max operating temperature)
Charge/discharge cycles	1,000,000 (between 51V and 25.5V) 2,000,000 (between 48V and 24V)
EMI compliance	EN 50121-3- 2:2016+A1:2019
Overvoltage protection specs	Module will send alarm, but no built-in protection to stop charge/discharge
Overcurrent protection specs	No alarm, no built-in protection
Overtemperature protection	Module will send alarm, but no built-in protection to stop charge/discharge
Accepted vibration level and damping requirement	EN 61373:2010+AC:2017, Shock and vibration class 18
Other mechanical installation and environmental issues for marine application	Environmental conditions EN 50125-1:2014
Safety issues	Fire protection EN 45545-2:2013+A1:2015

Table 9.3 shows the characteristics and specifications of a medium size SMES (500kJ, 200kW-2.5sec), [28], that has been developed by ASG. The SMES includes the superconducting coil, cryostat, cryocooler, compressor, chiller, and vacuum pump.

TABLE 9.3: MAIN CHARACTERISTICS AND SPECIFICATIONS OF SMES (500KJ, 200KW-2.5SEC)

Characteristics	**ASG SMES system** (excluding power-electronic converter)
Specific Energy (Wh/kg)	0.138
Specific power (W/kg)	200 (discharge 2.5s)
Energy Density (Wh/L)	0.05
Power Density (W/L)	77
Average power loss in the cooling system (kW)	7 at room temperature
Weight of the module (kg)	1,000
Volume of the module (L)	2,600
Coil operating temperature (K)	<16
Self-discharge	Some weeks
SMES quenching & protection	Quench detection system available during the stand-by mode
Expected strength of magnetic flux around the SMES module (e.g., on the surface of the external package)	B<5mT on the surface, B<0.5mT at 2m from the surface. These values can be reduced by a factor 10 introducing passive magnetic shielding (adding 500kg of materials) or active shielding (to be designed).
Overvoltage protection specs	Protection systems can be customized to check voltage, current and temperature and stop charge-discharge. The energy stored in the coil has to be discharged on a dump resistor.
Overcurrent protection specs	
Overtemperature protection	
Vibration level caused by the SMES system	Related to compressor, cryocooler, chiller and vacuum pump
Safety issues	The strength of the magnetic field needs to be evaluated to define "low field perimeter". General issues related to cryogenics, but no dangerous low temperature outside the cryostat. Management of high-pressure gas in the flex lines of the compressor needs to be addressed.

TABLE 9.4: PARAMETERS AND SPECIFICATIONS OF THE SMES SYSTEM DEVELOPED BY ASG.

Inner radius, mm	300
Height, mm	1200.6
Number of layers	10
Number of turns per layer	522
Length of cable, km	10.1
Voltage of the dc bus, V	750
Min Current, A	266.6
Max current, A	467
Field on conductor (at Imax), T	1.63
I/Ic ratio (at Imax)	0.6
Inductance, H	6.80
Total eneregy (at Imax), kJ	741
Deliverable energy, kJ	500.4
Dump resistance, Ω	2,14
Max adiabatic hot spot temp., K	95.6

For SMES system that uses the liquefied hydrogen, Table 9.5 provides the estimated parameters/characteristics which were evaluated by considering only the weight and volume of the superconducting coil of the SMES system.

TABLE 9.5: DATA AND CHARACTERISTICS EVALUATED BY ONLY CONSIDERING THE WEIGHT AND VOLUME OF THE SUPERCONDUCTING COIL OF THE SMES SYSTEM

Characteristics	**ASG SMES system** (excluding power-electronic converter)
Specific Energy (Wh/kg)	0.7
Specific power (W/kg)	1000 (discharge 2.5s)
Energy Density (Wh/L)	0.4
Power Density (W/L)	588
Weight of the module (kg)	200
Volume of the module (L)	340
Working temperature (K)	20

10 Appendix B

10.1 Description of analysed marine profile cases

10.1.1 Electric Ferry

This case is based on the data shown in Fig. 10.1. The Ferry basic electric topology is illustrated in Fig. 10.2. This marine application has been previously introduced in section 9. The fundamental cycle length is 2 hours with a sampling period of 6 seconds. Fig. 10.3 shows the HESS power profile for the ferry fundamental cycle. Based on the provide data, the following operation profile has been assumed:

- Operation hours: 16 hours, from 06:00 to 22:00.
- 32 trips per day, equivalent to 8 cycles per day
- No seasonal variation

Fig. 10.4 shows the estimated HESS power for a full day cycle considering the previous assumptions.

FIG. 10-1: FERRY POWER PROFILE DATA.

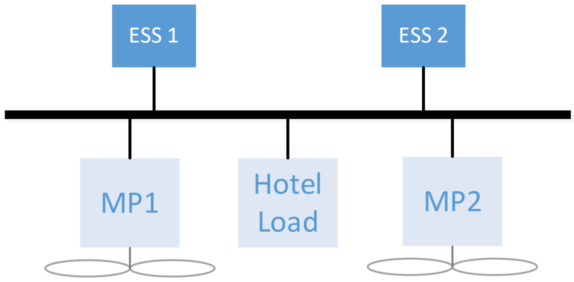


FIG. 10-2: FERRY BASIC ELECTRIC TOPOLOGY

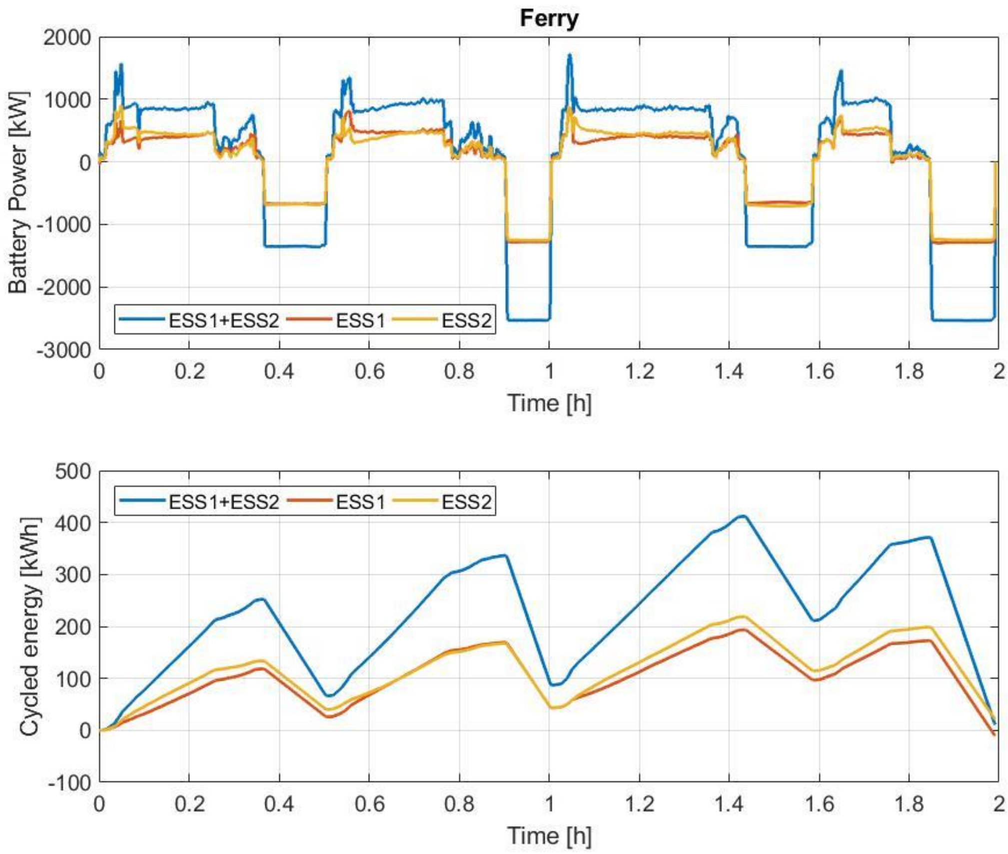


FIGURE 10-3: FERRY - FUNDAMENTAL CYCLE

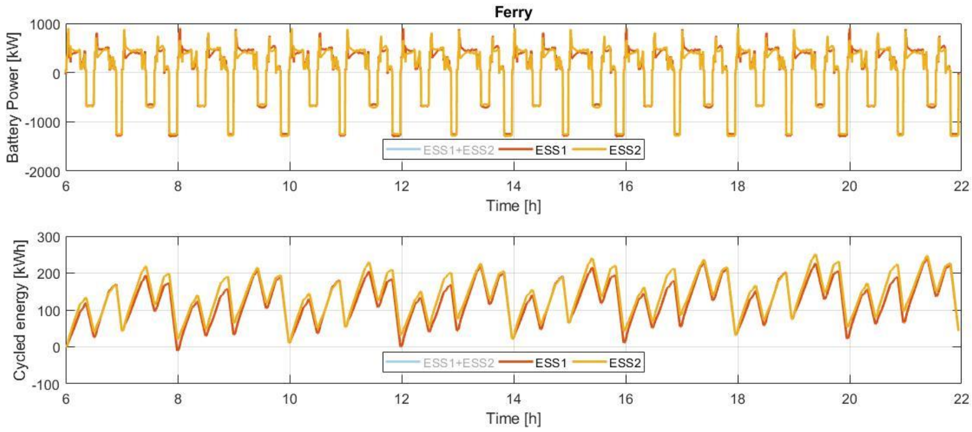


FIGURE 10-4: FERRY - FULL DAY CYCLE

The system is symmetrically composed by two ESS, and the following HESS requirements per ESS has been estimated:

- Minimum needed energy: 225 kWh
- Max. discharge power: 904 kW
- Max. charge power: 1,300 kW
- Annual energy throughput: 1,473 MWh
- Annual cycles: **6,547** cycles of 225 kWh depth.

Fig. 10.5 shows the HESS screening results for Ferry case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. While Fig. 10.6 also shows the HESS screening results for Ferry case with NMC batteries and supercapacitors, but when NMC design life of 10 years and SC design life of 7.5 years are considered.

For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation and the SC calendar life have been detected as limiting factors.

By analysing Fig.10.5 and Fig.10.6, it can be noted that the ferry profile can be considered as potential case study as HESS solution may provide benefits on capital cell cost reduction and reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 15, HESS solution will be the optimal solution.

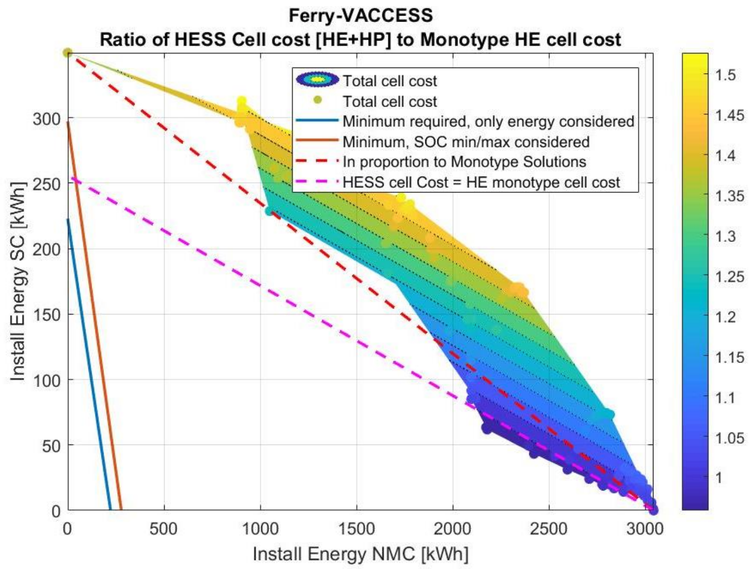


FIGURE 10-5: HESS SCREENING RESULTS FOR FERRY CASE WITH NMC BATTERIES AND SUPERCAPACITORS. RESULTS FOR NMC AND SC DESIGN LIFE OF 7.5 YEARS.

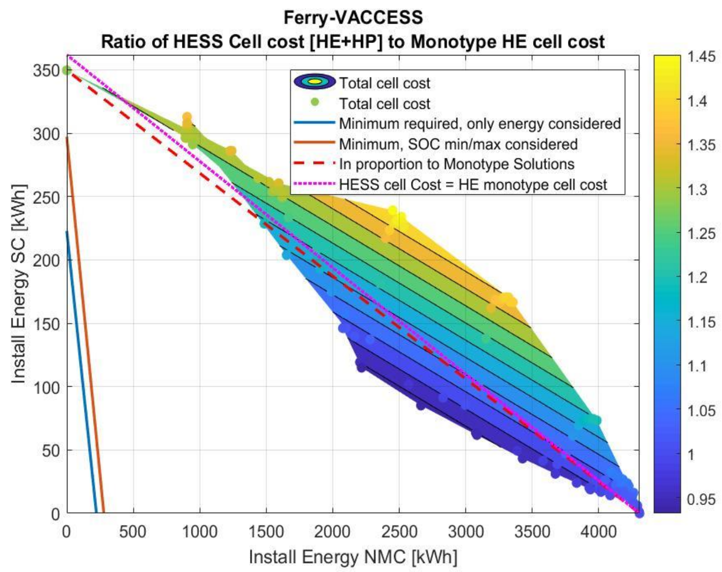


FIGURE 10.6: HESS SCREENING RESULTS FOR FERRY CASE WITH NMC BATTERIES AND SUPERCAPACITORS. RESULTS FOR NMC DESIGN LIFE OF 10 YEARS AND SC DESIGN LIFE OF 7.5 YEARS.

Fig. 10.7 shows the HESS screening results for Ferry case with NMC batteries and SMES. For this case, the main limiting factor are the NMC Charging power, the NMC cycling degradation and the SMES Charging power (for solutions composed by small SMES). This marine profile shows a potential case study for SMES & batteries in terms of reduction in installed capacity. To have a HESS as optimal solution in terms of capital cost reduction, a NMC to SMES cost ratio minor to 20 will be needed.

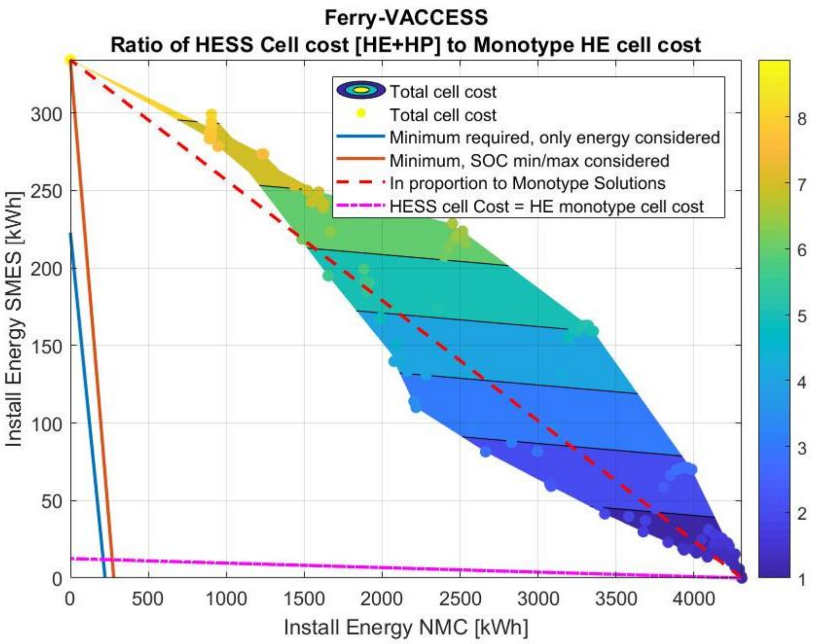


FIG. 10.7: HESS SCREENING RESULTS FOR FERRY CASE WITH NMC BATTERIES AND SMES. RESULTS FOR NMC DESIGN LIFE OF 10 YEARS AND SMES DESIGN LIFE EQUAL TO SHIP LIFETIME (30 YEARS).

10.1.2 Platform Support Vessel (PSV)

The power system is composed by 4 DGs and one ESS. Fig. 10.8 shows the PSV data. The first assessment has considered the provided total power time series and a low pass filter to estimate the HESS power profile. Fig. 10.9 shows possible PSV HESS power profiles for different low pass filter cut-off frequencies. The fundamental operational cycle length is 13 days, with a sampling period of 15 seconds. The operation profile for this marine application case assumed 80% operation time per year with no seasonal variation in the power time series. Different Low Pass Filter frequencies have been considered to get the HESS power profile.

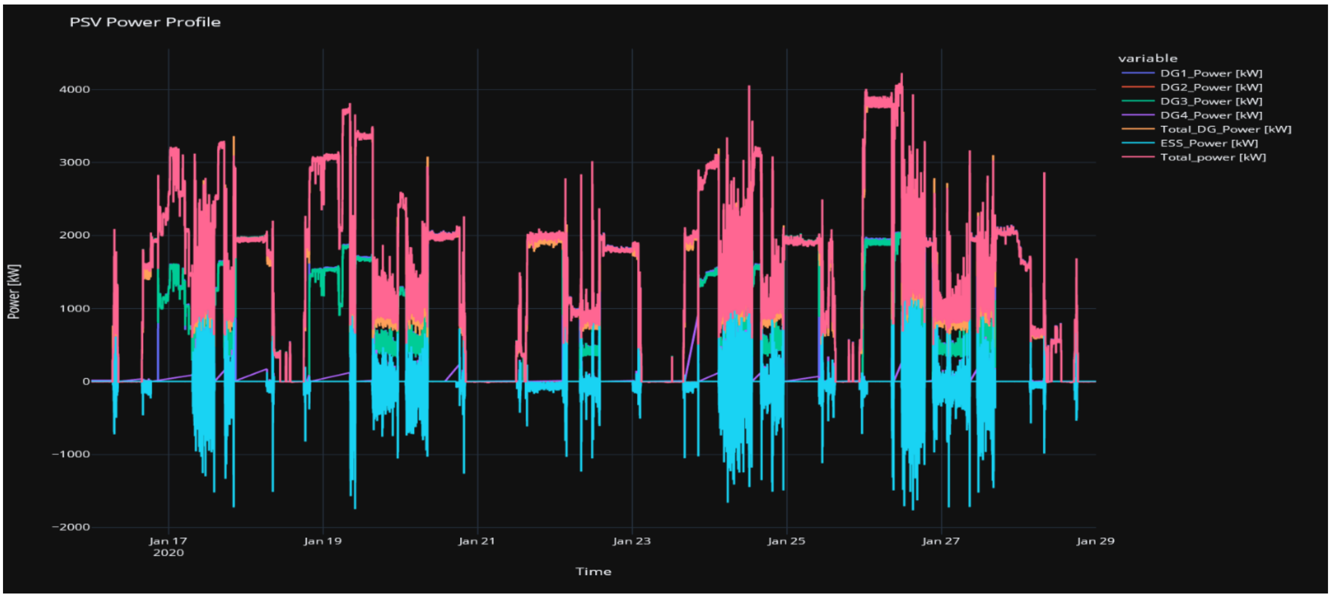


FIGURE 10-8: PSV POWER PROFILE DATA

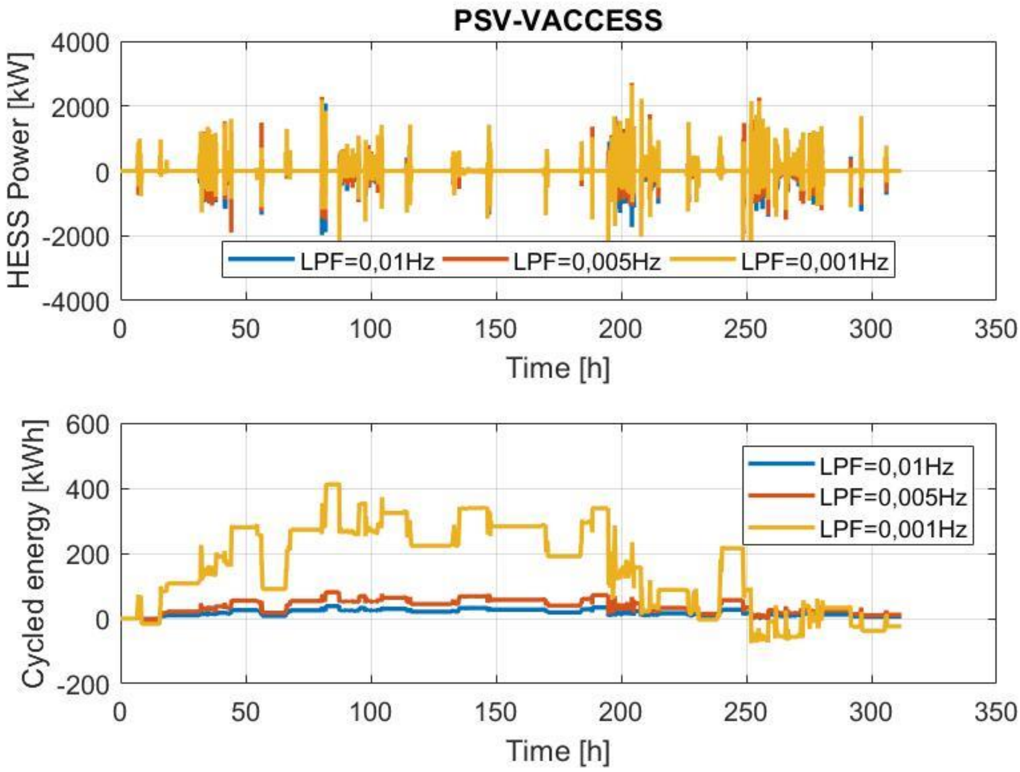


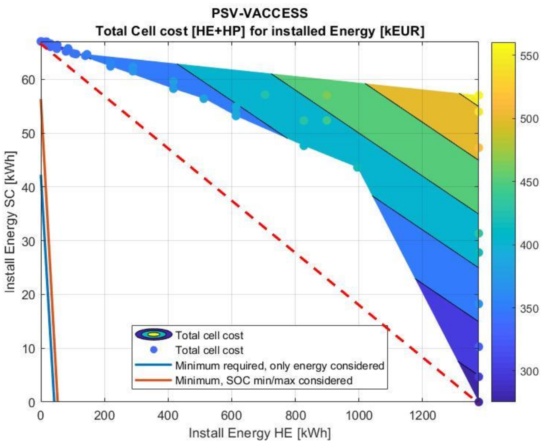
FIG. 10.9: POSSIBLE PSV HESS POWER PROFILE FOR DIFFERENT LOW PASS FILTERS

The following requirements per ESS for the PSV case have been identified when a LFP of 0.005Hz is considered:

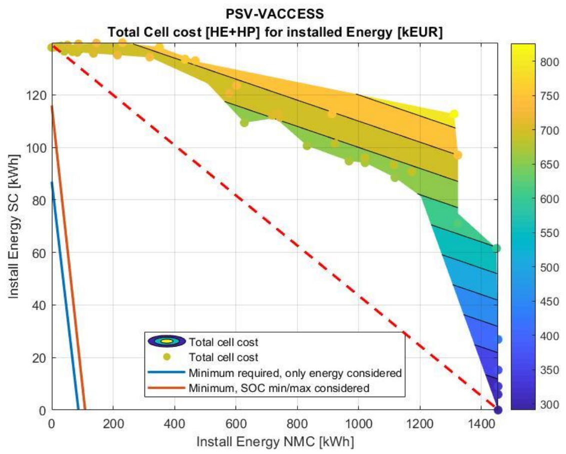
- Minimum needed energy: 86 kWh

- Max. discharge power: 2,714 MW
- Max. charge power: **1.9 MW**
- Annual Energy throughput: 160.5 MWh
- Annual cycles: **1,866** (@86 kWh)

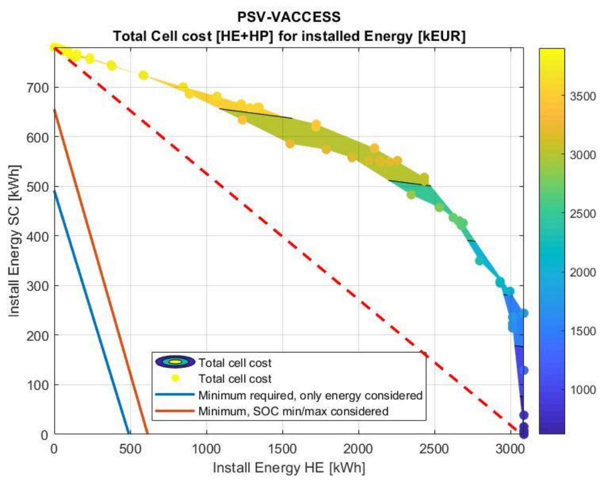
Fig. 10.10 shows the HESS screening results for PSV case with NMC batteries and SC, and for different low pass filter frequencies. Also, Fig. 10.11 shows the HESS screening results for PSV case with NMC batteries and SMES, and for a low pass frequency of 0.005 Hz. The detected limiting factors for this case are the NMC Peak Charging power, the NMC Cycling and calendar degradation and the SC Calendar Life. So far it is not a Potential case as observed from Fig. 10.10 and Fig. 10.11. However, the power time series needs further check after replacement of low pass filter strategy as method for HESS power estimation and by checking other HESS profiles by consider PSV total load with EMS at ship level.



a) LFP = 0.01Hz



b) LFP = 0.005Hz



c) LFP = 0.001 Hz

FIG. 10.10: HESS SCREENING RESULTS FOR PSV CASE WITH NMC BATTERIES AND SC.

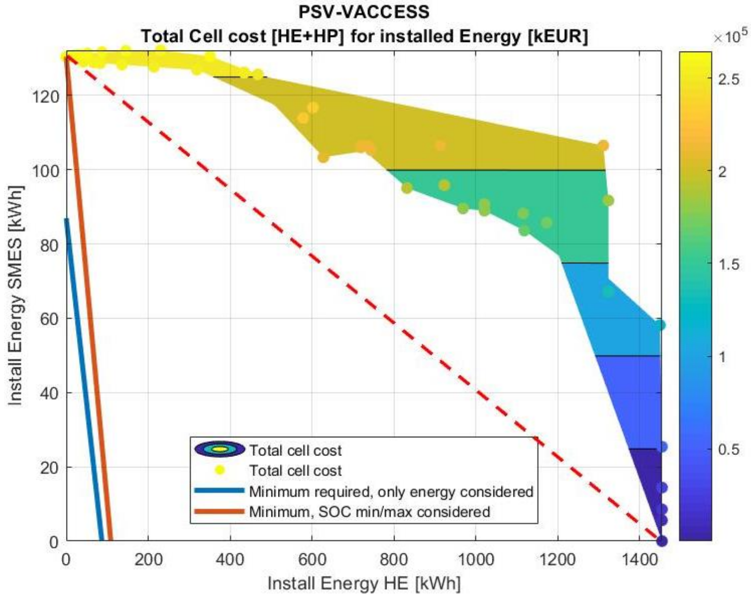


FIG. 10.11: HESS SCREENING RESULTS FOR PSV CASE WITH NMC BATTERIES AND SMES. (LFP = 0.005HZ)

10.1.3 Trawler

Fig. 10.12 shows the trawler power profile data. The first assessment has considered the provided Total power time series and a low pass filter to estimate the HESS power profile. Fig. 10.13 shows possible trawler HESS power profiles for different low pass filter cut-off frequencies. The fundamental operational cycle length is 2 days, with a sampling period of 15 seconds. The operation profile for this marine application case assumed 30% operation time per year with no seasonal variation in the power time series. Different Low Pass Filter frequencies have been considered to get the HESS power profile.

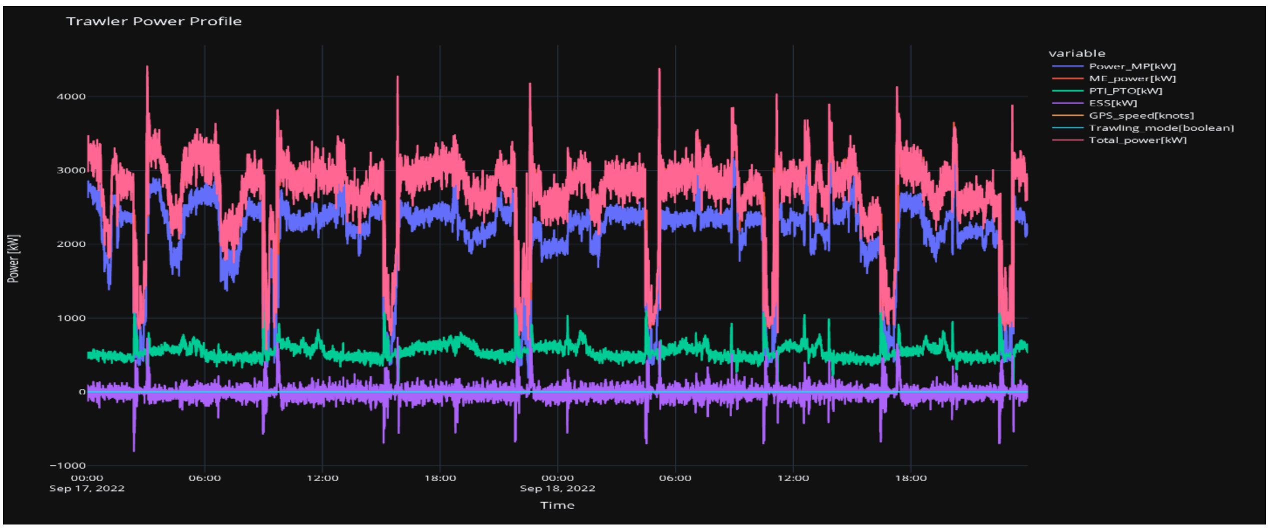


FIG. 10.12: TRAWLER POWER PROFILE DATA.

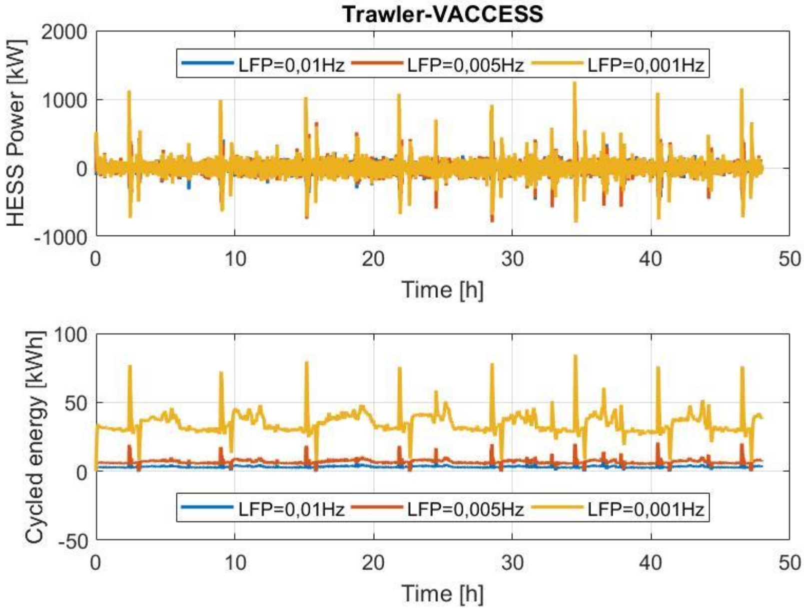
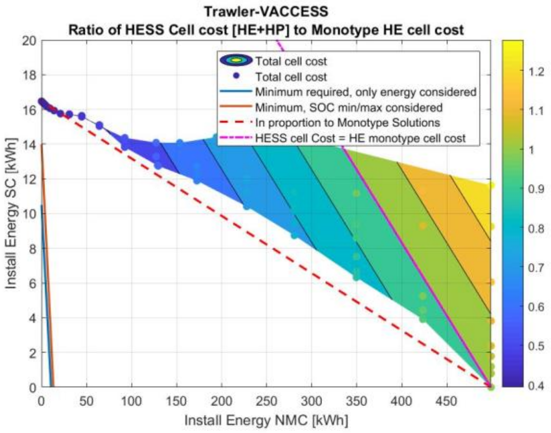


FIG. 10.13: POSSIBLE TRAWLER HESS POWER PROFILE FOR DIFFERENT LOW PASS FILTERS

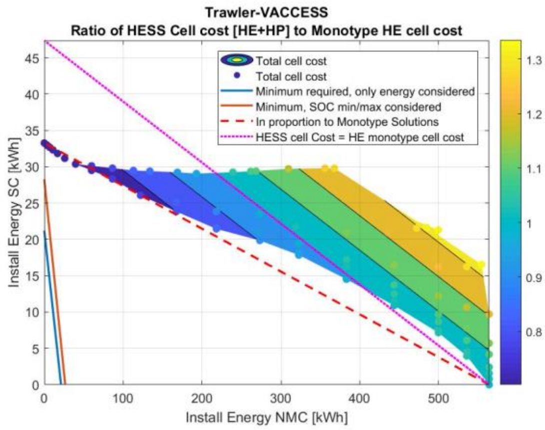
The following ESS requirements for the trawler case have been identified when a low pass filter cut-off frequency of 0.005 Hz is considered:

- Minimum needed energy: 21.2 kWh
- Max. discharge power: 1,113 kW
- Max. charge power: 796 kW
- Annual Energy throughput: 190.5 MWh
- Annual cycles: **8,986** (@21.2 kWh)

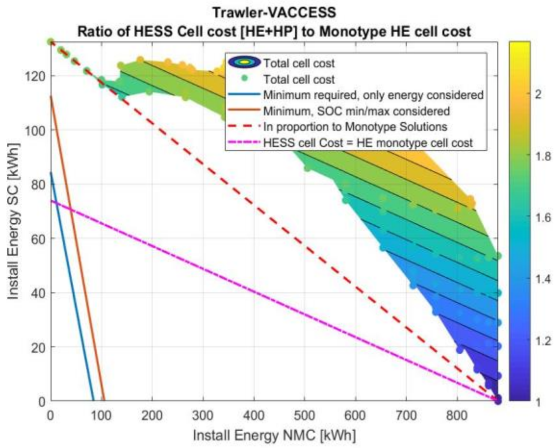
Fig. 10.14 shows the HESS screening results for trawler case with NMC batteries and SC, and for different low pass filter frequencies. The detected limiting factor for this case is the NMC charging power. This marine application seems to be a potential case study as observed from Fig. 10.14-b. The SC solution has been found to be optimal when LFP >= 0,005Hz. Further check can be done for other HESS profiles by considering trawler total load with EMS at ship level. Also, it has been detected that the HESS solution will be the optimal solution for NMC to SC cost ratios minor than 18.



a) LFP= 0.01Hz



b) LFP=0.005Hz



c) LFP=0.001Hz

FIG. 10.14: HESS SCREENING RESULTS FOR TRAWLER CASE WITH NMC BATTERIES AND SC.

10.1.4 Ro-Ro Ferry 1

This full electric Ro-Ro ferry marine application has been taken from reported marine application in (SEABAT, 2021). The Ro-Ro ferry mission profile has two main representative power profile operations, which corresponds with seasonal variations in the route for summer and winter. The summer profile, happening 335 days per year, when there is no ice, the ferry makes 37 crossings per day. During the heavy part of the winter, occurring 30 days per year, when there is ice, the ferry makes only 3 crossings per day on a different route which require significantly more energy. Fig. 10.15 shows the daily power time series for both, summer, and winter profiles, where the positive power represents the discharge power from the HESS. A 400-kW charger is available at each ferry station, so the HESS recharge the energy consumed after each trip section. The cycled energy, estimated from the power time series is also shown in Fig. 10.15. This profile has a fundamental cycle length (trip) of 40 minutes in summer; and 250 minutes in winter profiles. The sampling period of both profiles is 1 second.

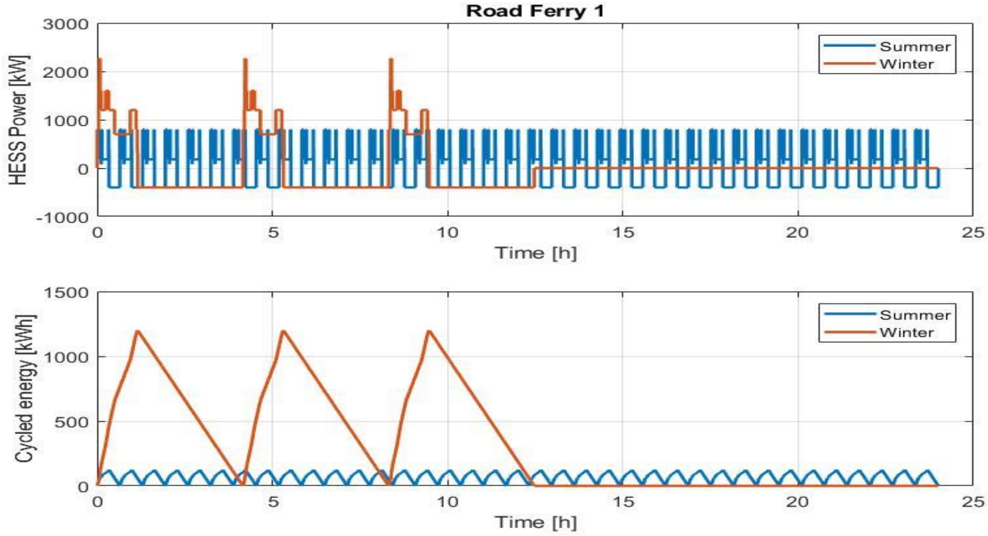


FIG. 10.15: RO-RO FERRY 1- SUMMER AND WINTER TYPICAL DAY PROFILE

The following ESS requirements have been identified:

- Minimum needed energy: 1,200 kWh
- Max. discharge power: 2,270 kW
- Max. charge power: 400 kW
- Energy throughput: 1,645 GWh
- Annual cycles: **1,371** (@1,200 kWh)

Fig. 10.16 shows the HESS screening results for Ro-Ro Ferry case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling, and calendar degradation and the SC calendar life have been detected as limiting factors.

By analysing Fig.10.16, it can be noted that the Ro-Ro ferry profile can be considered as potential case study as HESS solutions may provide benefits on capital cell cost reduction and reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 18, HESS solution will be the optimal solution.

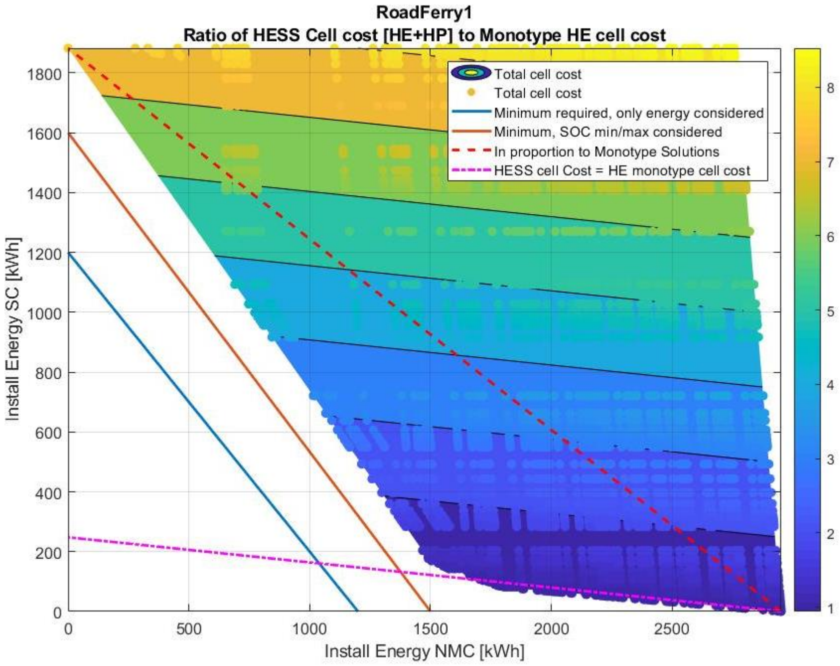


FIG. 10.16: HESS SCREENING RESULTS FOR RO-RO FERRY 1 CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS

Fig. 10.17 shows the HESS screening results for Ro-Ro Ferry case with NMC batteries and SMES. For this case, the main limiting factor are the NMC Charging power, the NMC cycling degradation and the SMES Charging power (for solutions composed by small SMES). This marine profile shows a potential case study for SMES & batteries in terms of reduction in installed capacity. To have a HESS as optimal solution in terms of capital cost reduction, a NMC to SMES cost ratio minor to 22 will be needed.

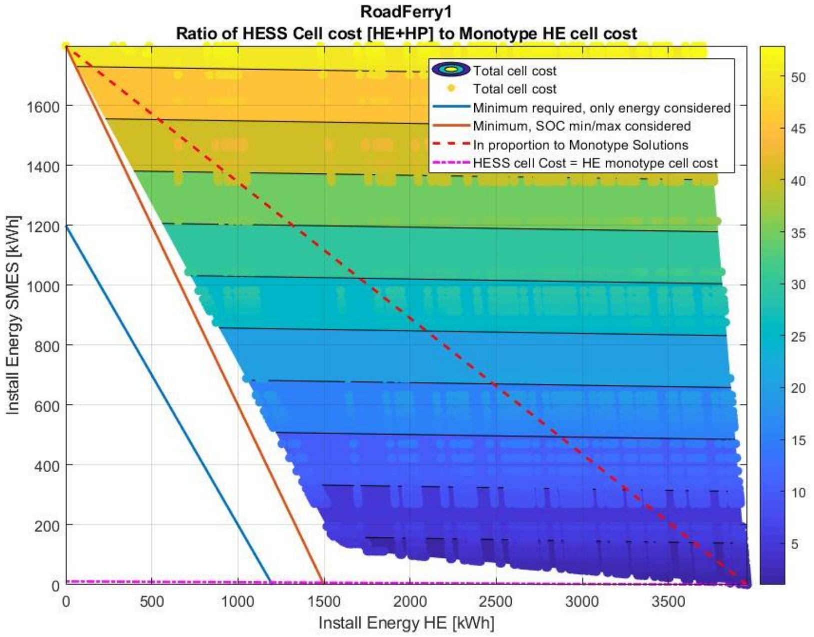


FIG. 10.17: HESS SCREENING RESULTS FOR RO-RO FERRY 1 CASE WITH NMC BATTERIES AND SMES. NMC DESIGN LIFE = 10 YEARS

10.1.5 Ro-Ro Ferry 2

This full electric Ro-Ro ferry marine application has been taken from reported marine application in (SEABAT, 2021). This Ro-Ro ferry 2 profile performs 34 round trips per day, with a charging station on each side. Fig. 10.18 shows the daily power time series for the considered Ro-Ro ferry 2 application. It is assumed that approximately 5% of the time the weather conditions will result in a larger power and energy demand during the trip, which is represented by the last two cycles in the operational profile.

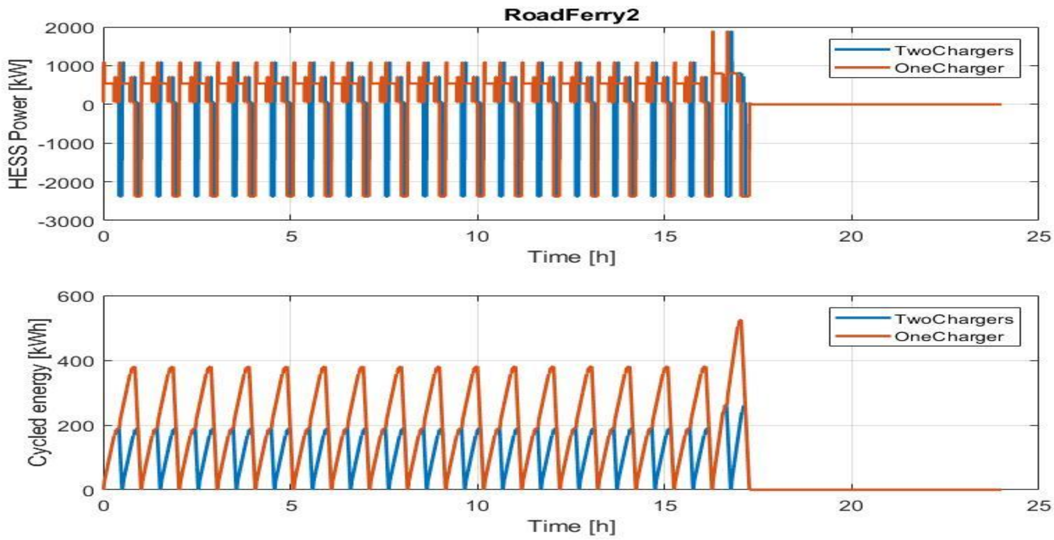


FIG. 10.18: RO-RO FERRY 2- TYPICAL DAY PROFILES

The Ro-Ro ferry 2 mission profile accounts for the case that one of the charging stations is not operational, without having an impact on the operational schedule of the ferry. It is assumed that approximately 5 days per year there is a problem with one of the charging stations. Therefore, there is an operational profile provided for 2 active chargers and for 1 active charger. This profile has a fundamental cycle length (trip) of 30 minutes and not seasonal variation. The sampling period of both profiles is 30 seconds.

The following ESS requirements have been identified:

- Minimum needed energy: 525 kWh
- Max. discharge power: 1,900 kW
- Max. charge power: 2,380 kW
- Annual Energy throughput: 2.4169 GWh
- Annual cycles: 4,604 (@525 kWh)

Fig. 10.19 shows the HESS screening results for Ro-Ro Ferry 2 case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation, and the SC calendar life have been detected as limiting factors.

It can be noted, from Fig. 10.19, that the Ro-Ro ferry 2 profile can be considered as potential case study as HESS solutions may provide benefits on capital cell cost reduction and reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 15, HESS solution will be the optimal solution.

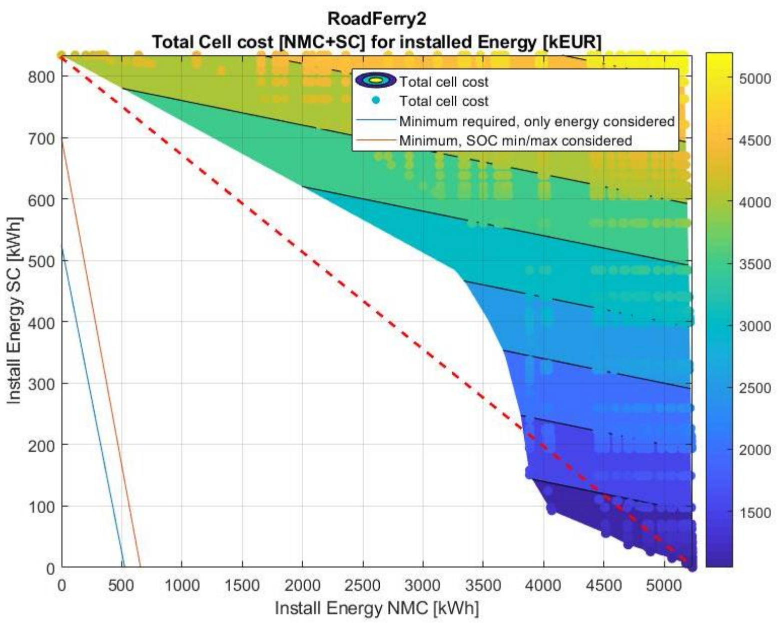


FIG. 10.19: HESS SCREENING RESULTS FOR RO-RO FERRY 2 CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

10.1.6 Harbour Tug

This full electric harbour tug marine application has been taken from reported marine application in (SEABAT, 2021). The harbour tug performs on average three standard jobs per day of about 80 minutes each. After every job the vessel has time to charge the batteries with a 1,000kW charger. Once every week the three standard jobs are followed by a larger/heavier job, which requires approximately 185 minutes, and more than the double of the energy need for the standard job. Fig. 10.20 shows the Harbour Tug's typical day profiles. The data has a sampling period of 30 seconds.

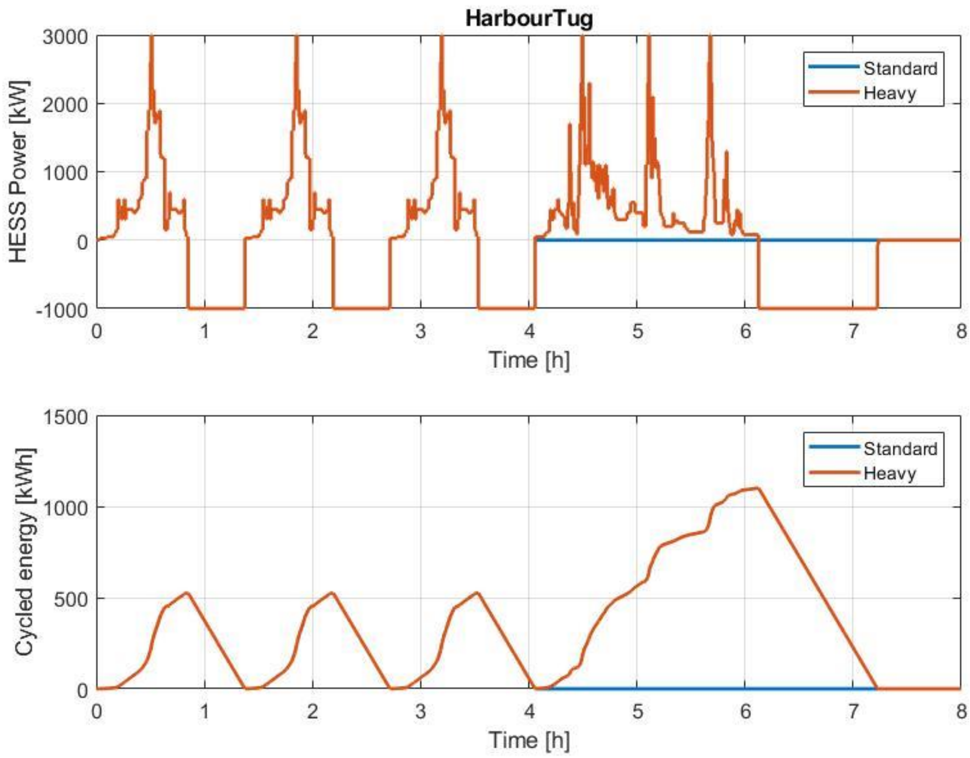


FIG. 10.20: HARBOUR TUG'S TYPICAL DAY PROFILES

The following ESS requirements have been identified:

- Minimum needed energy: 1,100 kWh
- Max. discharge power: 3,000 kW
- Max. charge power: 1,000 kW
- Annual Energy throughput: 632 GWh
- Annual cycles: 575 (@ 1,100 kWh)

Fig. 10.21 shows the HESS screening results for the harbour tug case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation, and the SC calendar life have been detected as limiting factors.

It can be noted, from Fig. 10.21, that this application can be marginally considered as potential case study as HESS solutions may provide benefits on reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 4, HESS solution will be the optimal solution. However, Fig. 10.22 shows the HESS screening results for Harbour Tug case with NMC batteries and SC, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries and between 5 and 7.5 years for SC. This shows a better case for the harbour tug application, with more HESS solution to provide further reduction in the lifetime installed capacities.

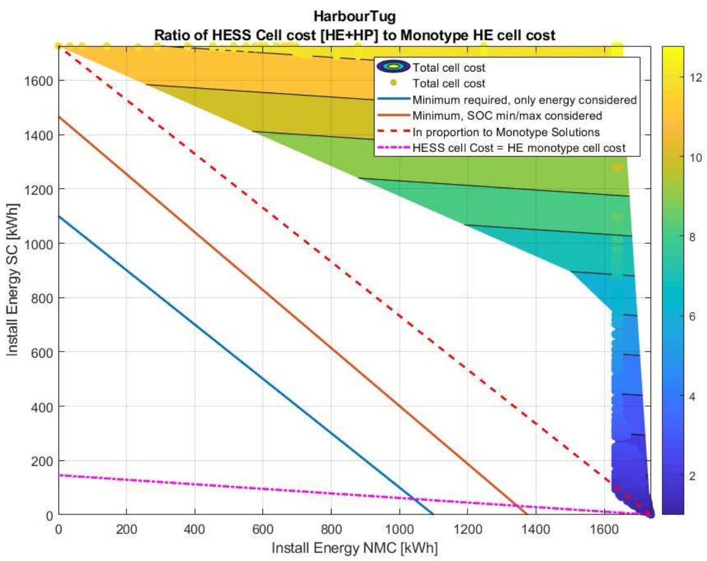


FIG. 10.21: HESS SCREENING RESULTS FOR HARBOUR TUG CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

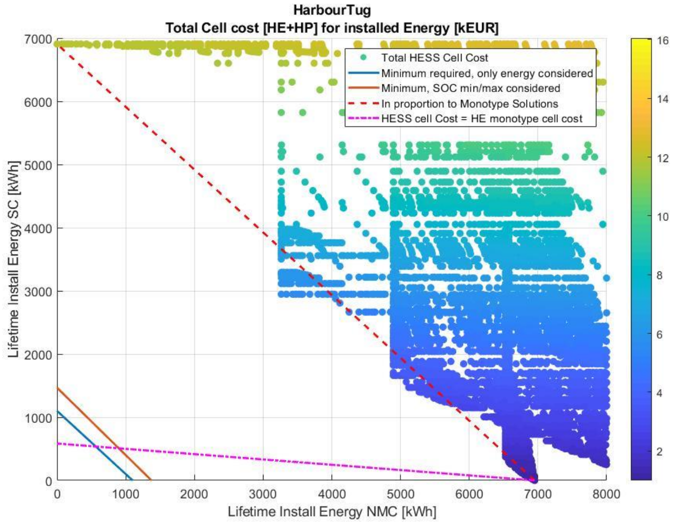


FIG. 10.22: HESS SCREENING RESULTS FOR HARBOUR TUG CASE WITH NMC BATTERIES AND SC. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFE: NMC ➔ 5-15 YEARS AND SC ➔ 5- 7.5 YEARS.

10.1.7 Urban Ferry

This full electric urban ferry marine application has been taken from reported marine application in (SEABAT, 2021). The urban ferry application corresponds to a small vessel operating on a fixed route in an urban area. The route has multiple stops where passengers get on or off the ferry. The mission profile is characterized by two operational profiles: short versus long trips. At one of the stops there is a charging station with a maximum charge power of 600 kW. The ferry makes 8 trips per day which in normal conditions require about 60 minutes and 35 kWh per trip, which will be charged in a few minutes at 400 kW. In 5% of the time there is a trip which takes longer (around 115 minutes) and requires more power, resulting in an energy requirement of 136 kWh. To charge the batteries sufficiently again in the available time after this larger trip the maximum charge power of 600 kW is required. Both data in the power profiles has a sampling period of 30 seconds. Fig. 10.23 shows the urban Ferry typical day profiles.

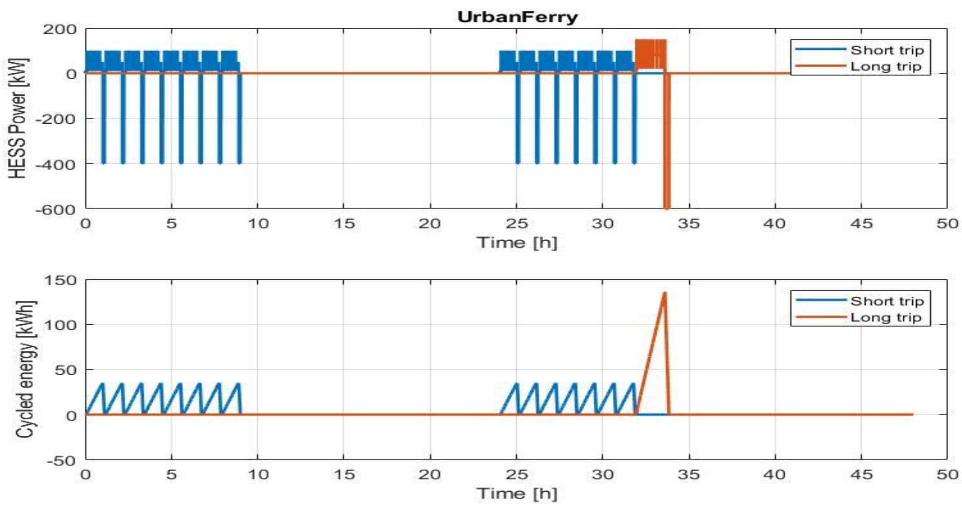


FIG. 10.23: URBAN FERRY – TYPICAL DAY PROFILE

The following ESS requirements have been identified:

- Minimum needed energy: 136 kWh
- Max. discharge power: 150 kW
- Max. charge power: 600 kW
- Annual Energy throughput: 120.63 GWh
- Annual cycles: 887 (@136 kWh)

Fig. 10.24 shows the HESS screening results for the urban ferry case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation, and the SC calendar life have been detected as limiting factors. It can be noted, from Fig. 10.24, that this application does not show a potential case study.

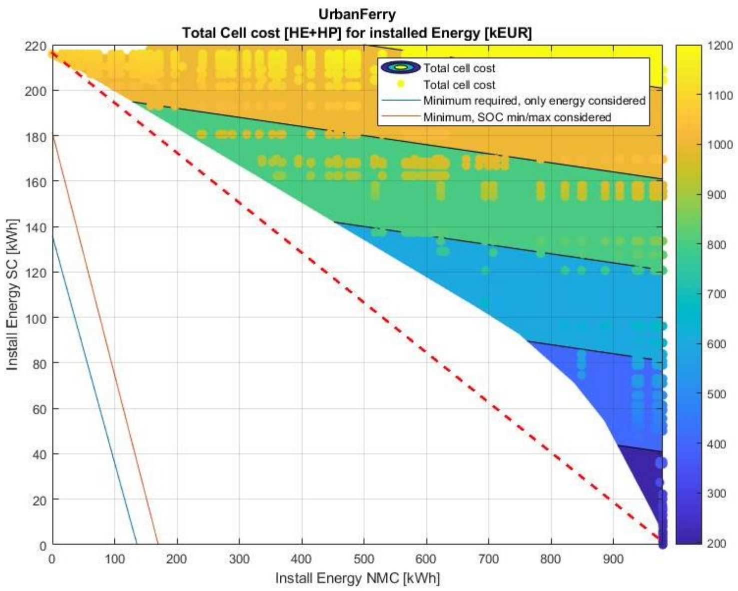


FIGURE 10.24: HESS SCREENING RESULTS FOR URBAN FERRY CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

10.1.8 Water Bus

This full electric water bus marine application has been taken from reported marine application in (SEABAT, 2021). Fig. 10.25 shows the water bus operational profiles for short and long trips. The water bus will perform 16 short trips per day which requires about 350 kWh. Approximately 5% of the time there is a trip which takes longer and requires more power, resulting in an energy requirement of 850 kWh. The long trip takes around 120 minutes, while the short trip takes around 60 minutes, including the charging time. A charging station with maximum charging power of 1.4 MW is available.

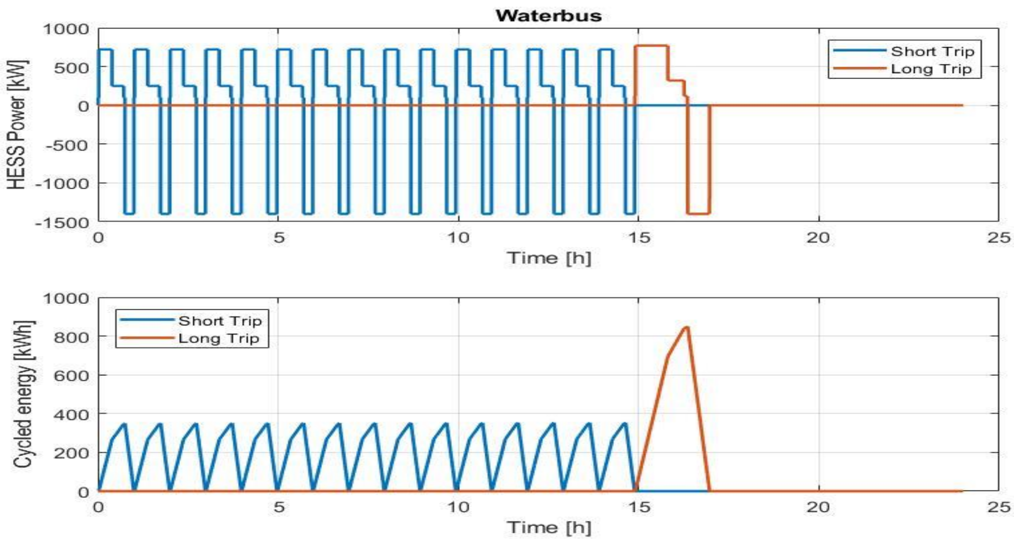


FIG. 10.25: WATER BUS - TYPICAL DAY PROFILE

The following ESS requirements have been identified:

- Minimum needed energy: 850 kWh
- Max. discharge power: 770 kW
- Max. charge power: 1,400 kW
- Annual Energy throughput: 2,228 GWh
- Annual cycles: 2,621 (@ 850 kWh)

Fig. 10.26 shows the HESS screening results for the water bus case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation, and the SC calendar life have been detected as limiting factors. It can be noted, from Fig. 10.26, that this application can be considered as potential case study as HESS solutions may provide benefits on reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 8, HESS solution will be the optimal solution. Additionally, Fig. 10.27 shows the HESS screening results for water bus case with NMC batteries and SC, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries and between 5 and 7.5 years for SC. This shows a better case for the water bus application, with more HESS solution to provide further reduction in the lifetime installed capacities.

On the other hand, Fig. 10.28 shows the HESS screening results for the water bus case with NMC batteries and SMES, and when NMC design life of 10 years is considered. While Fig. 10.29 shows the HESS screening results for water bus case with NMC batteries and SMES, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries For the HESS solution composed by NMC and SC technologies, the NMC charging power and the NMC cycling degradation have been detected as limiting factors. It can be noted that this application can be considered as potential case study for SMES and batteries as HESS solutions may provide benefits on reduced installed capacity.

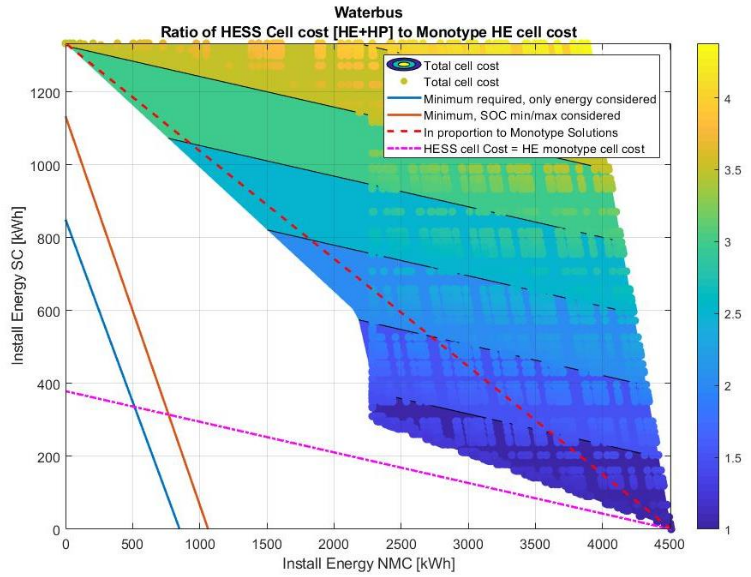


FIG. 10.26: HESS SCREENING RESULTS FOR WATER BUS CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

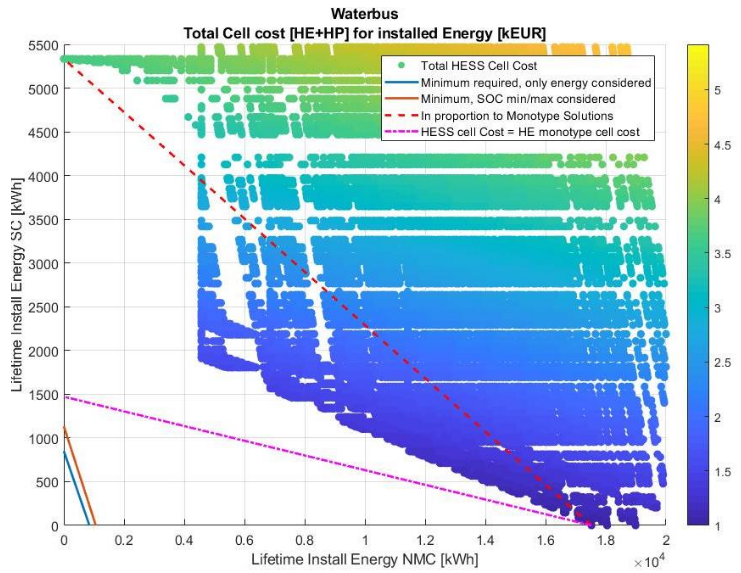


FIG. 10.27: HESS SCREENING RESULTS FOR WATER BUS CASE WITH NMC BATTERIES AND SC. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFE: NMC ➔ 5-15 YEARS AND SC ➔ 5- 7.5 YEARS.

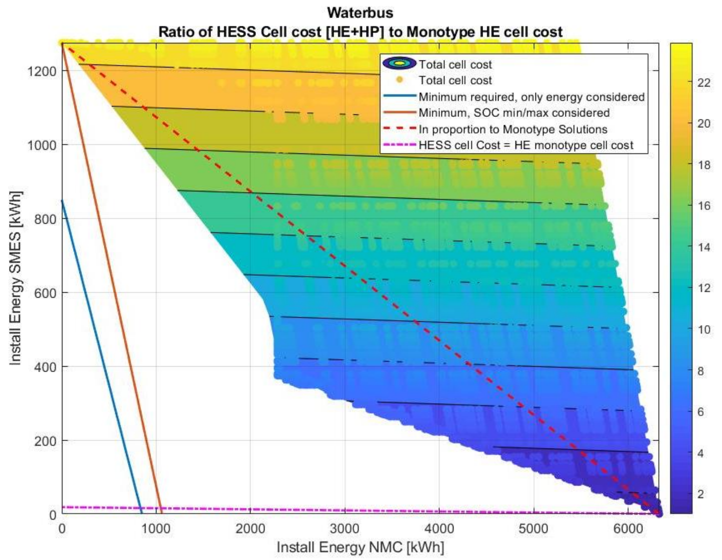


FIG. 10.28: HESS SCREENING RESULTS FOR WATER BUS CASE WITH NMC BATTERIES AND SMES. (NMC DESIGN LIFE = 10 YEARS)

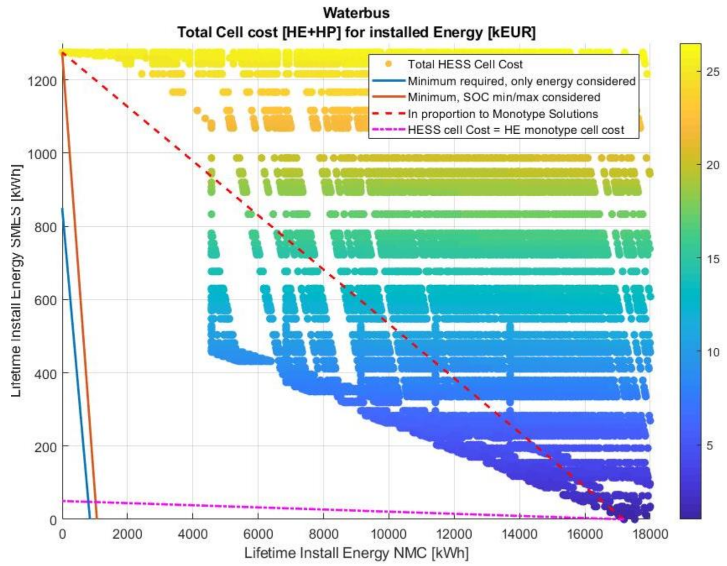


FIG. 10.29: HESS SCREENING RESULTS FOR WATER BUS CASE WITH NMC BATTERIES AND SMES. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFE: NMC → 5-15 YEARS AND SMES → SHIP LIFETIME (30 YEARS).

10.1.9 Fish Carrier

The fish carrier vessel is a DG hybrid marine system, which has been taken from reported marine application in (SEABAT, 2021). Fig. 10.30 shows the fundamental profiles, which corresponds to the two main functionalities of the HESS in the fish carrier marine system: Peak Shaving and Spinning Reserve. The fundamental cycle length for peak shaving is 1 minute, while for spinning reserve is 37 minutes. Both profile data has a sampling period of 30 seconds. The assumed daily operational profile is shown in Fig. 10.31. This mission profile assumes 150 operational days per year. The peak shaving is emulated as 1 MW square waveform with about 1 minute period. The spinning reserve is used once every two days. The spinning reserve consist of 2.7 MW for 10 minutes.

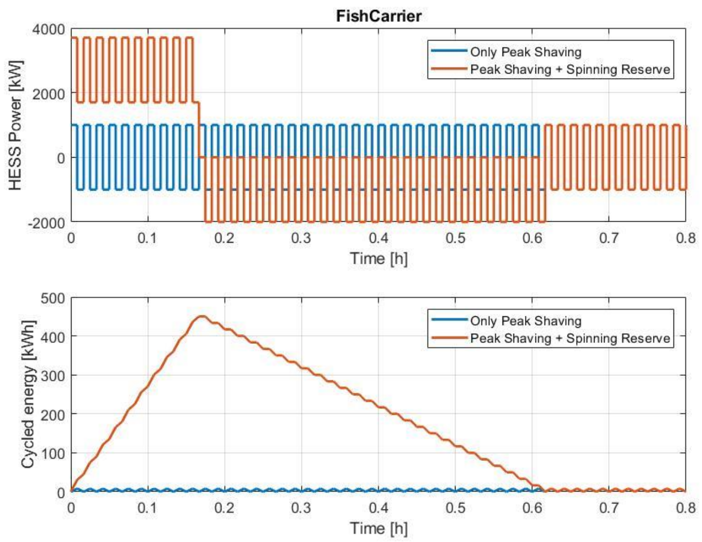


FIG. 10.30: FISH CARRIER - FUNDAMENTAL CYCLES

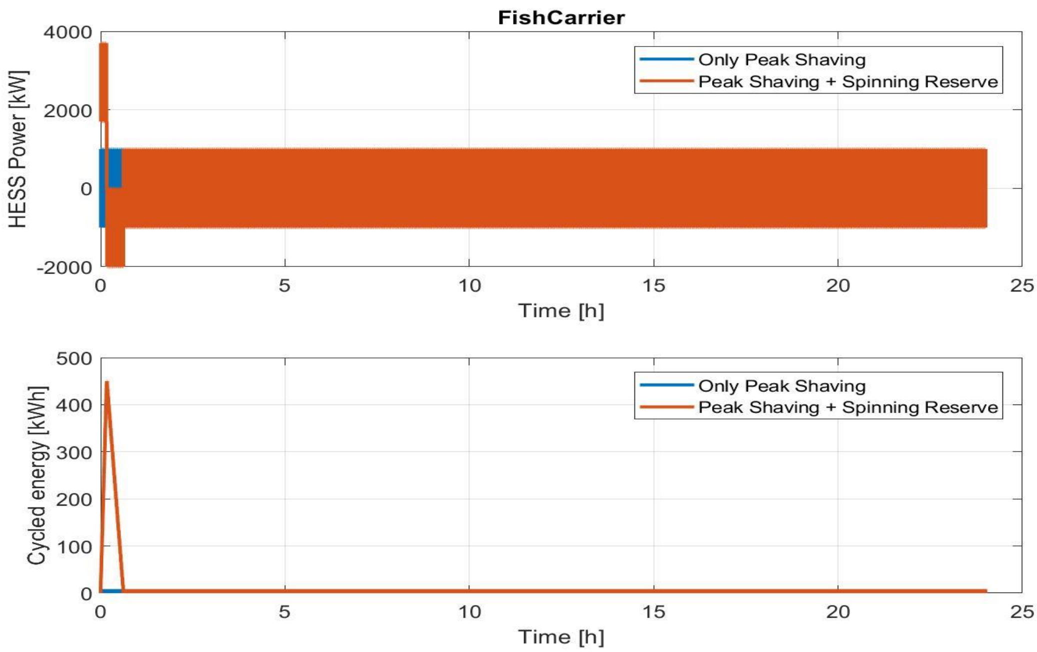


FIG. 10.31: FISH CARRIER - TYPICAL DAILY PROFILES

The following ESS requirements have been identified:

- Minimum needed energy: 450 kWh
- Max. discharge power: 3,700 kW

- Max. charge power: 2,000 kW
- Annual Energy throughput: 1.812 GWh
- Annual cycles: **4,026** (@450 kWh)

Fig. 10.32 shows the HESS screening results for fish carrier case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging and discharging power, the NMC cycling degradation and the SC calendar life have been detected as limiting factors. Additionally, Fig. 10.33 shows the HESS screening results for fish carrier case with NMC batteries and SC, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries and between 5 and 7.5 years for SC.

By analysing Fig.10.32 and Fig.10.33, it can be noted that the fish carrier profile can be considered as a very good potential case study as HESS solutions may provide very high benefits on capital cell cost reduction and reduced installed capacity.

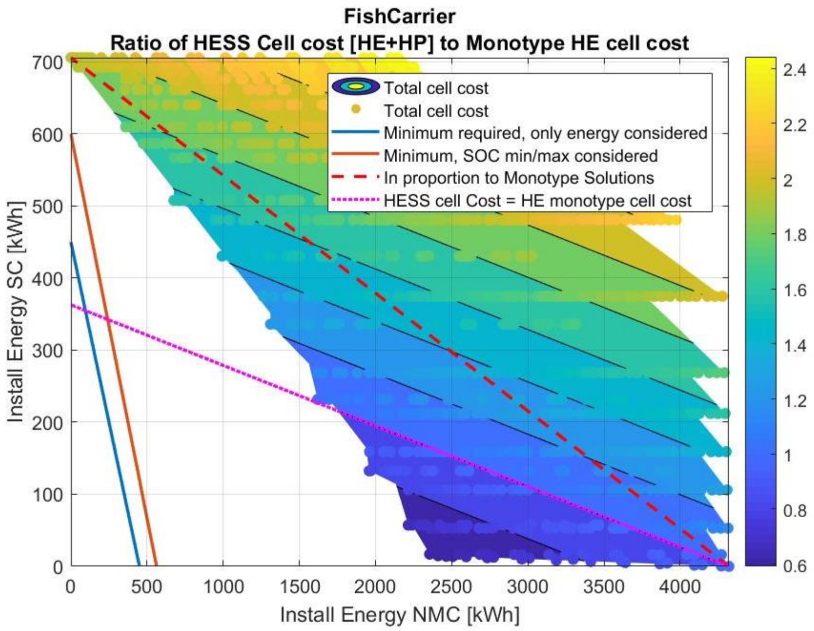


FIG. 10.32: HESS SCREENING RESULTS FOR FISH CARRIER CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

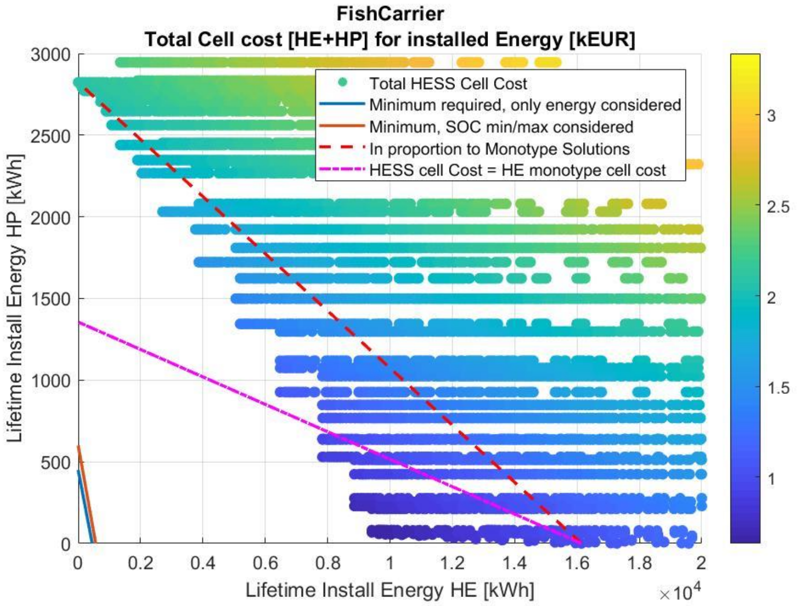


FIG. 10.33: HESS SCREENING RESULTS FOR FISH CARRIER CASE WITH NMC BATTERIES AND SC. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFE: NMC ➔ 5-15 YEARS AND SC ➔ 5- 7.5 YEARS.

10.1.10 Fishing Vessel

The fishing vessel is a DG hybrid marine system, which has been taken from reported marine application in (SEABAT, 2021). Fig. 10.34 shows the fundamental profiles, which corresponds to the two main functionalities of the HESS in the fishing vessel: Peak Shaving and boost function. The fundamental cycle length for peak shaving is 20 minutes, while for boost function is 60 minutes. Both profile data has a sampling period of 30 seconds. The assumed daily operational profile is shown in Fig. 10.35. This mission profile assumes 310 operational days per year. The peak shaving is emulated as 285 kW square waveform with about 20 minutes period. Boost function used twice a day, which is emulated by discharging 630 kW for 18 minutes and then charging 315 kW for 36 minutes.

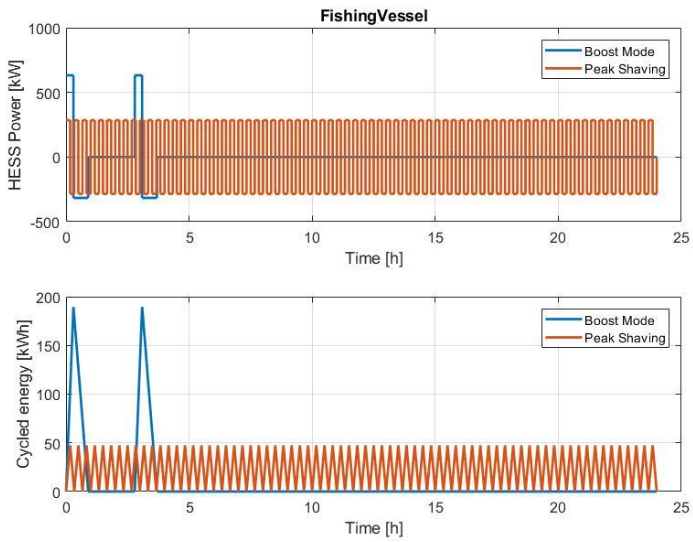


FIG. 10.34: FISHING VESSEL - FUNDAMENTAL CYCLES

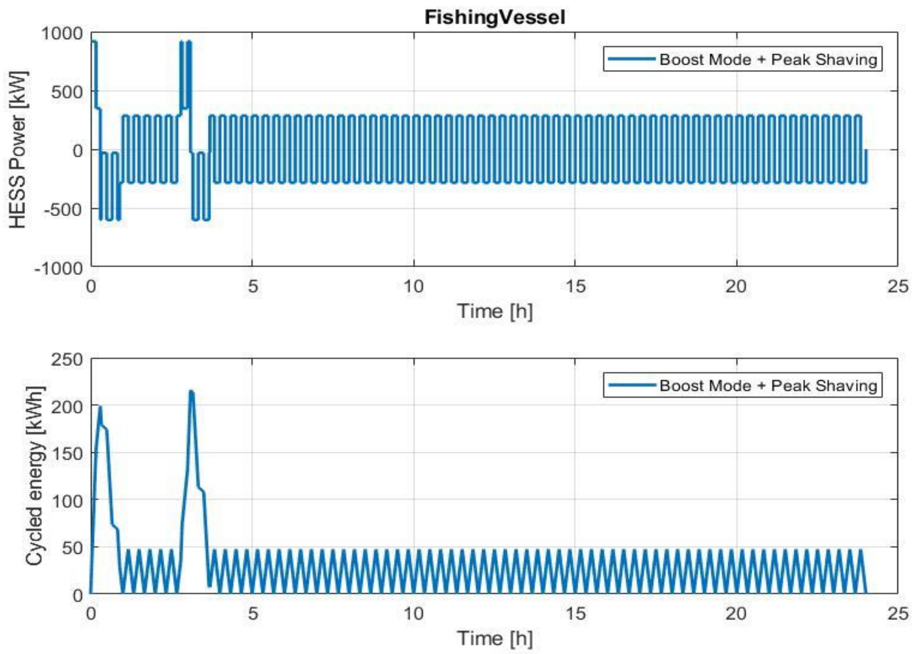


FIG. 10.35: FISHING VESSEL - TYPICAL DAY PROFILE

The following ESS requirements have been identified:

- Minimum needed energy: 216 kWh
- Max. discharge power: 917 kW
- Max. charge power: 601 kW
- Annual Energy throughput: 1.098 GWh
- Annual cycles: **5,084** (@216 kWh)

Fig. 10.36 shows the HESS screening results for fishing vessel case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC charging power, the NMC cycling degradation and the SC calendar life have been detected as limiting factors. By analysing Fig.10.36, it can be noted that the fishing vessel profile can be considered as a marginal potential case study as HESS solutions may provide benefits on reduced installed capacity. Also, it has been calculated that for NMC to SC cost ratio minor that 8, HESS solution will be the optimal solution.

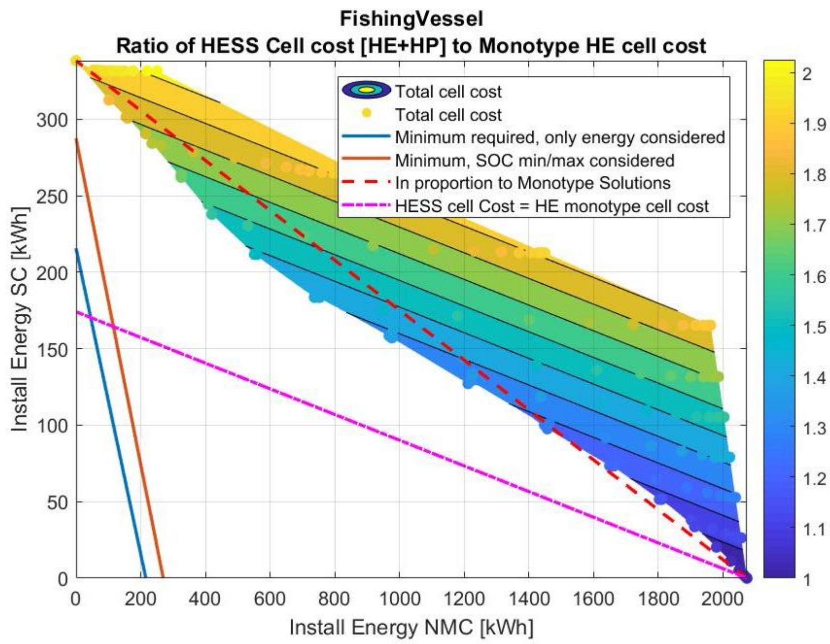


FIG. 10.36: HESS SCREENING RESULTS FOR FISHING VESSEL CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

10.1.11 Bulk carrier + Crane operation

This marine application is supported by simulation data provided by Sintef Ocean. Fig. 10.37 shows the crane load fundamental cycle, while Fig. 10.38 shows the fundamental cycle for the HESS power profile, which has been calculated from the crane load by subtracting its average power. The fundamental cycle length is 4,000 seconds, and the simulation data has a sampling period of 1 second. The assumed operation profile consists of 14 fundamental cycles each time (≈15.5 hours), with the Crane operation happening once a month. Additionally, the HESS is also design for provide spinning reserve functionality. The spinning reserve consist of proving 800 kW for 10 minutes and it is assumed to be needed 60 times per year.
Fig. 10.39 shows the typical profile for the bulk carrier with crane operation.

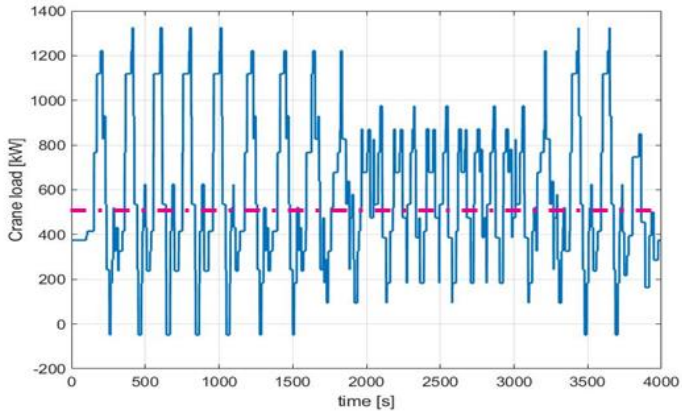


FIG. 10.37: CRANE LOAD - FUNDAMENTAL CYCLE

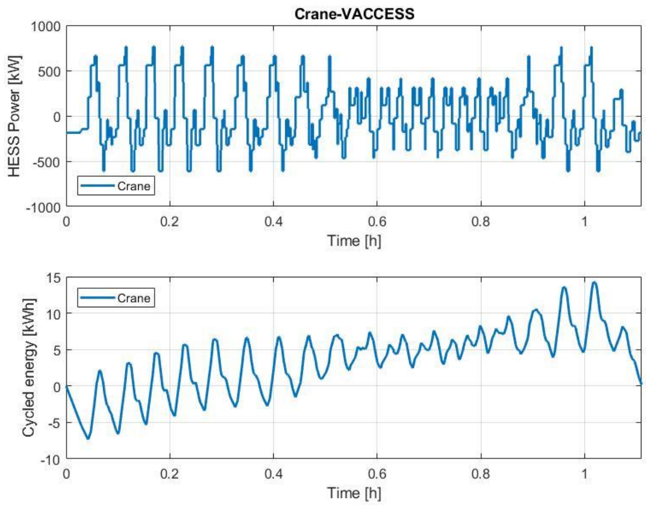


FIG. 10.38: BULK CARRIER WITH CRANE OPERATION - HESS FUNDAMENTAL CYCLE

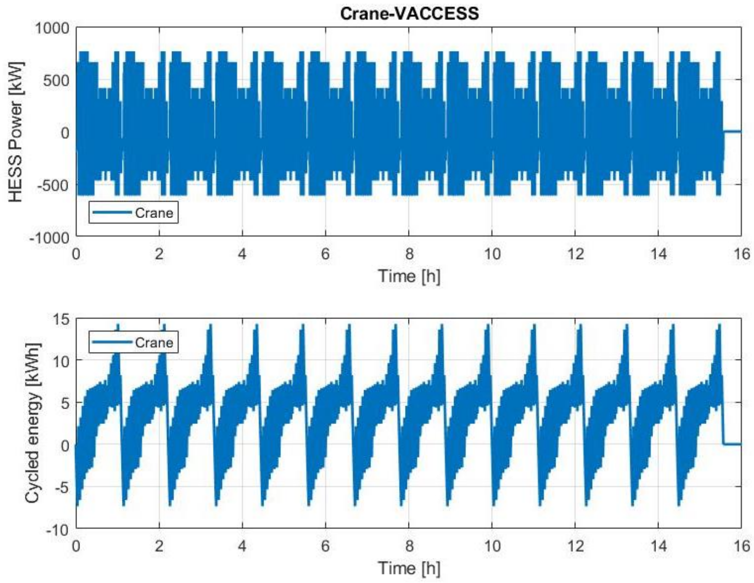


FIG. 10.39 BULK CARRIER WITH CRANE OPERATION - TYPICAL PROFILE

The following ESS requirements have been identified:

- Minimum needed energy: 133 kWh
- Max. discharge power: 800 kW
- Max. charge power: 610 kW
- Annual Energy throughput: 32.63 MWh
- Annual cycles: **245** (@133 kWh)

Fig. 10.40 shows the HESS screening results for the bulk carrier with crane operation case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC continuous charging/discharging power, the NMC cycling degradation, the SC calendar life and the SC peak charging power have been detected as limiting factors. It can be noted, from Fig. 10.40, that this application can be marginally considered as potential case study as HESS solutions may provide marginal benefits on reduced installed capacity. However, Fig. 10.41 shows the HESS screening results for Bulk carrier with crane operation case with NMC batteries and SC, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries and between 5 and 7.5 years for SC. This shows a better case for this application, with more HESS solution to provide further reduction in the lifetime installed capacities and capital cell cost. Also, it has been calculated that for NMC to SC cost ratio minor than 18, HESS solution will be the optimal solution.

Further variations can be analysed for this case study by considering different genset levelling values in the estimation of the HESS crane profile.

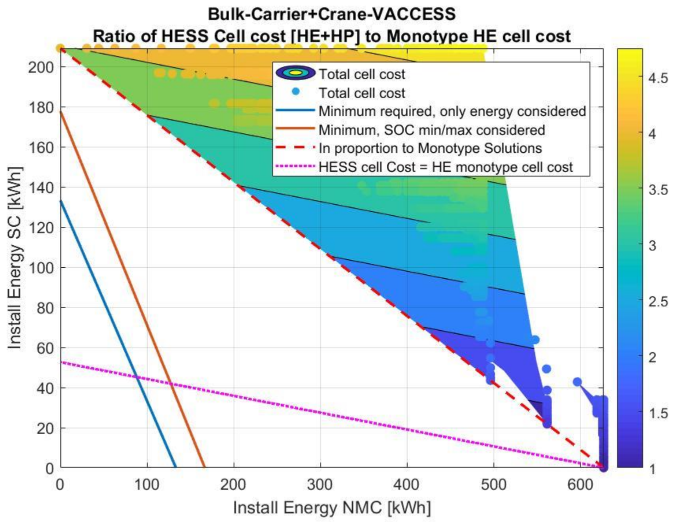


FIG. 10.40: HESS SCREENING RESULTS FOR BULK CARRIER CRANE OPERATION CASE WITH NMC BATTERIES AND SC. (SC & NMC DESIGN LIFE = 7.5 YEARS)

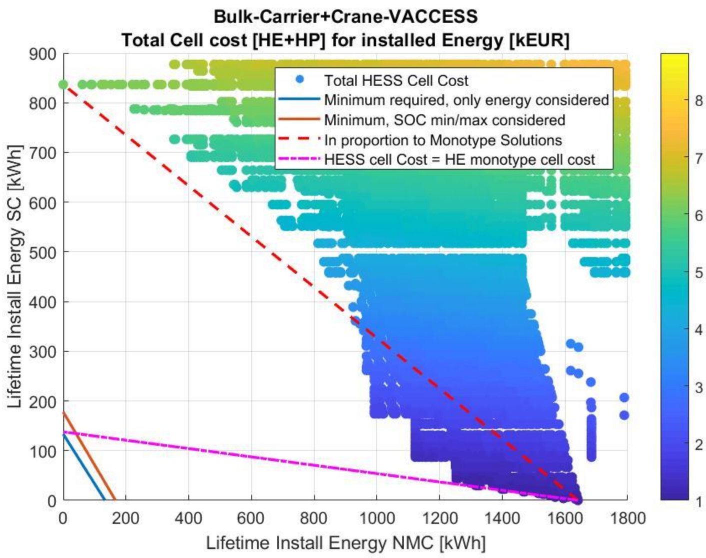


FIG. 10.41: HESS SCREENING RESULTS FOR BULK CARRIER CRANE OPERATION CASE WITH NMC BATTERIES AND SC. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFE: NMC → 5-15 YEARS AND SC → 5- 7.5 YEARS.

10.1.12 Offshore Service Vessel – active heave compensation system

This marine application is supported by active heave compensation (AHC) system simulation data provided by Sintef Ocean and log data provided by Vard for PSV case. The first assessment estimates the ESS power time series by applying Low Pass Filter to the PSV total power data. AHC power simulation has been superimposed to the total power time series. Fig. 10.42 shows Possible OSV-AHC HESS power profile for different low pass filter cut-off frequencies. The fundamental Cycle length is 62 hours, with a sampling period of 1 second. The operation profile assumes 70% operation time per year with no seasonal variations in the power load.

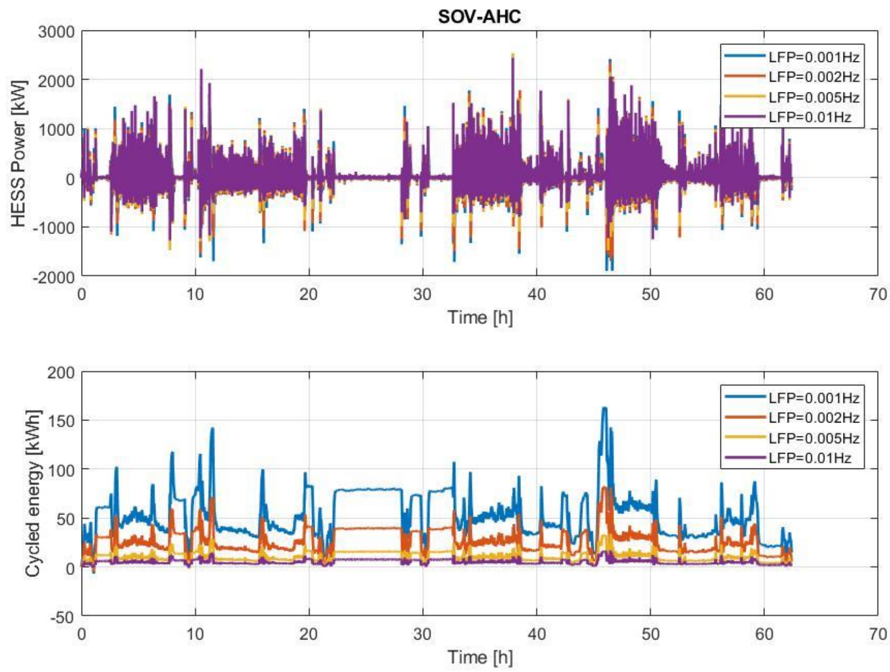


FIG. 10.42: POSSIBLE OSV-AHC HESS POWER PROFILE FOR DIFFERENT LOW PASS FILTER CUT-OFF FREQUENCIES

The following ESS requirements have been identified when a low pass filter cut-off frequency of 0.01Hz is considered:

- Minimum needed energy: 18 kWh
- Max. discharge power: 2,438 kW
- Max. charge power: 1,273 kW
- Annual Energy throughput: 236.11 MWh
- Annual cycles: 13,117 (@ 18 kWh)

Fig. 10.43 shows the HESS screening results for the OSV + AHC case with NMC batteries and supercapacitors, and when NMC and SC design life of 7.5 years are considered. For the HESS solution composed by NMC and SC technologies, the NMC peak charging/discharging power and SC peak discharging power have been detected as limiting factors. It can be noted, from Fig. 10.43, that this application can be considered as potential case study as HESS solutions may provide benefits on reduced installed capacity. Even more, Fig. 10.44 shows the HESS screening results for OSV + AHC case with NMC batteries and SC, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries and between 5 and 7.5 years for SC. This shows a better case for this application, with more HESS solution to provide further reduction in the lifetime installed capacities and capital cell cost.

On the other hand, Fig. 10.45 shows the HESS screening results for the OSV + AHC case with NMC batteries and SMES, and when NMC design life of 10 years is considered. While Fig. 10.46 shows the HESS screening results for OSV + AHC case with NMC batteries and SMES, but considering the Lifetime installed capacity for different design life: between 5 and 15 years for NMC batteries. It can be noted that this application can be considered as potential case study for SMES and batteries as HESS solutions may provide benefits on reduced installed capacity.

Further analysis can be performed to check for ESS extra usage in this application case.

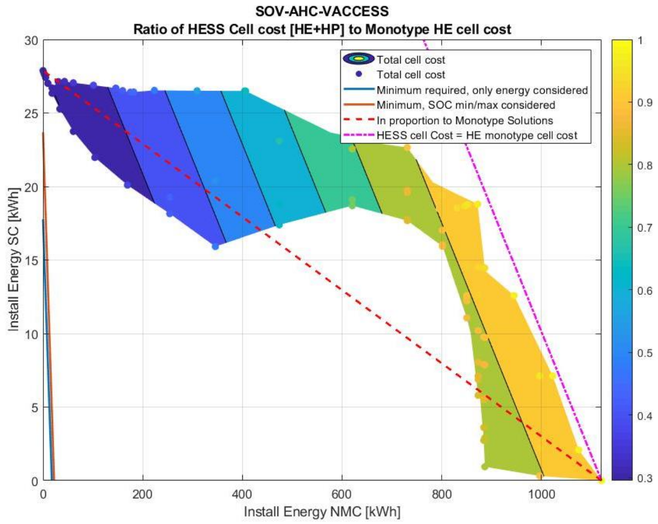


FIG. 10.43: HESS SCREENING RESULTS FOR OSV-AHC CASE WITH NMC BATTERIES AND SC. GENSET LFP = 0,01HZ. (SC & NMC DESIGN LIFE = 7.5 YEARS)

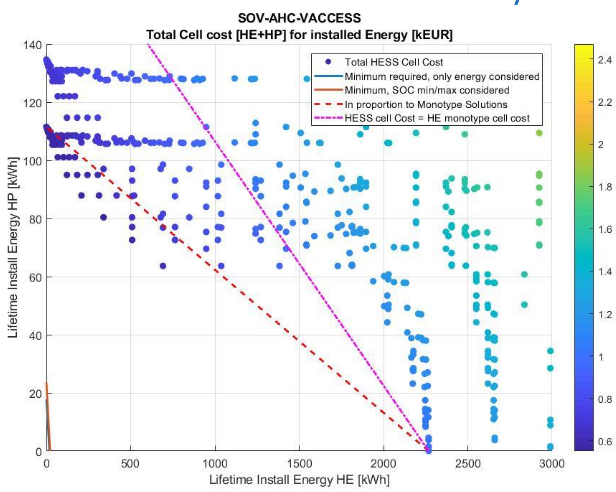


FIG. 10.44: HESS SCREENING RESULTS FOR OSV-AHC CASE WITH NMC BATTERIES AND SC. LIFETIME INSTALLED CAPACITY FOR DIFFERENT DESIGN LIFES: NMC➔ 5-15 YEARS AND SC➔ 5- 7.5 YEARS.

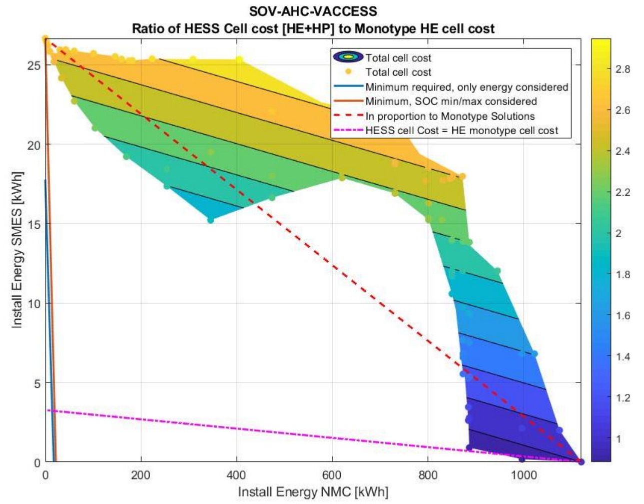


Fig. 10.45: HESS screening results for OSV-AHC case with NMC batteries and SMES. Genset LFP = 0,01Hz. (NMC Design life = 10 years)

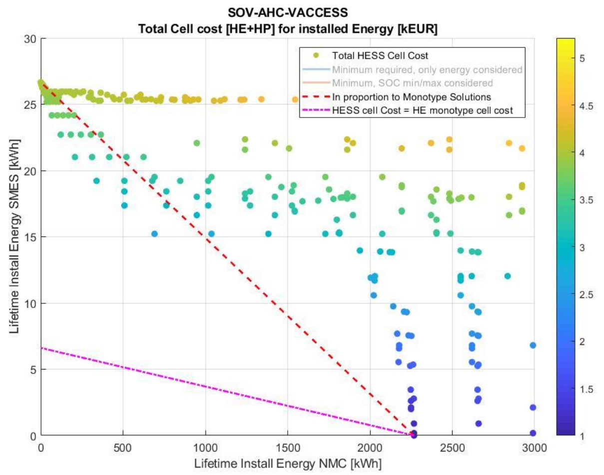


Fig. 10.46: HESS screening results for OSV-AHC case with NMC batteries and SMES. Lifetime installed capacity for different design lifes: NMC → 5-15 years and SMES = 30 years (ship lifetime).