D5.1 Market readiness level of different storage solutions and the next steps to increase the TRL

Document Identification			
Status	Final	**Due Date**	31.01.2025
Version	1.0	**Submission Date**	31.01.2025

Related WP	5	**Document Reference**	D5.1
Related Deliverables		**Dissemination Level**	SEN- Sensitive
Lead Participants	SKT	**Lead Author**	Skeleton Technologies
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Keywords
TRL development roadmap of ESS, market readiness, competitors, market entry barriers, cost of goods sold, supply chain security, technology sovereignty, certification, Supercapacitor, SMES, …

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Abbreviations and acronyms

AHC	Active Heave Compensation
BiSCCO	Bismuth strontium calcium copper oxide
BMS	Battery Management system
CAPEX	Capital Expenditure
COGS	Cost of Goods Sold
DNV	Det Norske Veritas
DPS	Dynamic Positioning Systems
ECAs	Emission Control Areas
EDLCs	Electrochemical Double-Layer Capacitors
EMI	Electromagnetic Interference
ESR	Equivalent Series Resistance
ESS	Energy Storage systems
FMEA	Failure Modes and Effects Analysis
GFR	Glass Fibre reinforced Resin
HESS	Hybrid Energy Storage System
HTS	High temperature superconductor
IMO	International Maritime Organization
IWT	Inland waterway transport
LFP	Lithium iron phosphate
LiBs	Lithium-ion Batteries
LTO	Lithium Titanate Oxide
MRI	Magnetic resonance imaging
NMC	Nickel manganese cobalt
OSV	Offshore Support Vessel
ReBCO	Rare earth barium copper oxide
SMES	Superconducting Magnetic Energy Storage system
SOLAS	International Convention for the Safety of Life at Sea
SOx	Sulfur oxides
STANAG	Standardization agreement
TRL	Technological Readiness Level

Abstract

This deliverable report (D5.1) serves as an overview of market readiness level of novel storage solutions such as supercapacitors and superconducting magnetic energy storage systems and the next steps to increase their technological readiness level in the marine sector. For that in-depth analysis was done of the readiness level of the supply chains, critical raw materials, market and competitors. Roadmaps for both technologies are presented, and a go-to-market strategy is described. This deliverable report will be updated with interface requirements between the new products and on-board systems using input from other WP5 tasks such as T5.3.

Introduction

The shipping industry is responsible for a significant percentage of global greenhouse gas emissions, which has resulted in a growing need to reduce emissions from shipping. The EU decision to achieve climate neutrality by 2050 contains several important milestones to be obtained during the process. Such as reducing carbon intensity of all ships by 40% by 2030 compared to 2008 baseline. This has already led towards sustainable energy by increased development of electric vessels. Total CO_2 emissions from shipping are approximately 3% of global emissions. Electric vessels, whether they are ships, boats, or ferries, provide a clean and efficient alternative to traditional fossil-fuel-powered vessels. In several places emission control is regulated by the harbor port, so that vessels can only maneuver without internal combustion engines during entry, stay or exit.

This leads to development in short-term energy storage systems, which are paving the way for more efficient and environmentally friendly solutions for vessels to operate. When used onboard ships in combination with Li-ion batteries or future advanced batteries, they can lead to optimally sustainable designs for future vessels. Short-term energy storage systems (e.g. supercapacitors and SMES) can deliver and draw peak and transient load power, allowing long-term energy storage systems to supply the total average power consumed by the vessel, thus prolonging the service life of the long-term systems.

Overview of supercapacitor systems:

Supercapacitor is a type of short-term energy storage system based on cells that store energy in an electric field between two electrodes. Inside the cell porous materials have a large specific surface area, which increases the amount of energy that can be stored. Whereas batteries store energy chemically in intercalation and insertion materials, which is a much slower process, supercapacitors store energy physically in the form of surface charges within the electrochemical double layer. In the scope of this project Electrochemical Double-Layer Capacitors (EDLCs) are used. 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. This results in high capacitance.

The physical energy storage mechanism of supercapacitors enables them to be charged and discharged within less than a second for over 1,000,000 times, within a wide temperature range (-40 to 65°C). This is possible due to the absence of chemical reactions which are slower processes, and which lead to quicker degradation of the active materials over time. Batteries age when they are used (cycled) supercapacitors on the other hand age when they hold charge without cycling. The available surface area of supercapacitors electrodes results in high power density, however, also is a limiting factor for energy density when compared to electrochemical storage devices. Novel active materials such as Skeleton Technologies Curved Graphene have a larger available surface area, specifically tuned microporosity, and electric conductivity than activated carbons, which enables to increase 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 conventional Lithium-ion batteries. Supercapacitor has also exceptionally low equivalent series resistance (ESR), which results in high round-trip efficiencies. This makes them ideal for applications where a quick response with power peak is required, such as power quality and peak-power shaving applications. As supercapacitors are static systems with high safety as there is no risk of thermal runaway, they are therefore low-maintenance systems. Also, no critical raw materials are being used for producing supercapacitors, such as lithium and nickel.

Since the voltage of supercapacitors changes during charge or discharge, a power converter is always needed to match the energy storage system's output voltage with the voltage of the power system. Converters should be voltage-sourced because supercapacitors behave electrically like capacitors and are typically current-controlled devices when connected to the shipboard power system.

As WP1 determined three main use cases where short-term energy storage systems will be analyzed, supercapacitor system was sized according to the power profiles. Since Skeleton Technologies' supercapacitor system has been designed to be modular to match clients' needs, the building blocks of the system remain similar.

The first use case is the electrical ferry that short-term energy system is used in parallel with large battery pack. The second use case was OSV and short-term energy system to be used in active heave compensation, much more suitable application in terms of energy content need. And finally, in the third case it was dimensioned for a trawler resulting in a very small system. The physical lab testing prototype (T3.5) mostly resembles the second use case in terms of dimensions and technical specifications.

Overview of Superconducting Magnetic Energy Storage systems:

SMES is a technology developed in 1980 to reinforce grids as presented in the A Luongo & all review paper [1] or more recently to provide pulse power supplies for other applications [2]. In this system the energy is stored into a magnetic field of a compact superconducting coil. The SMES system acts as a current source of power system. The power is released by the discharge on a load through a converter. As it does not require chemical reactions, the SMES system can be reloaded very fast and has nearly no ageing. Its lifetime is designed with the same requests for any basic conducting electric grids devices for a lifetime of over 40 years. The stored energy is totally reversible and can be returned with high efficiency (>97%). However, this performance is possible at the cost of maintaining the coil at cryogenic temperatures generally below 20K. As a short-term energy storage technology, the SMES can provide the benefits of voltage stabilization (momentary voltage spikes and sags), load fluctuation compensation, and improved power quality of grids that fit well with pulses power required onboard electrical ships. The main studies have been carried out on SMES systems based on NbTi wires in the past and more recently on HTS (ReBCO or BiSCCO superconducting tapes). The two last conductors can operate under high magnetic fields typically 15T and at high temperature 20K-30K [3]. However, the performance of these conductors is highly anisotropic versus the magnetic field orientation that requires a complex design optimization of the shape of the coil. If an operation at such a high magnetic field increases the power and energy density of the system, it obviously generates some high stray fields that can interact negatively with the environment. If they are not compatible, the level of the stray field can be limited by a shielding at the cost of a decrease of energy density associated with an increase of cryogenic losses. In addition, the cost of these conductors is still high, and their supply limited. It impacts negatively on the cost and on the availability of the HTS tape-based system. Recently MgB_2 conductor has been developed to be used and tested in a SMES system [4]. The maximum magnetic field achievable by MgB_2 conductor (maximum 5T at 20K) is lower than the one reachable with ReBCO or BiSCCO tapes. The drawback of an operation at the lower magnetic field is a decrease of the specific stored power or energy but it may also ease its integration onboard a ship by a reduction of the level of the stray magnetic field. Its main advantages are that the MgB_2 conductor is less expensive, manufactured with sustainable materials and mechanically strong in all directions. It can be produced in large quantities. It also presents an anisotropic behavior versus magnetic field that simplifies the design of the SMES coil. All these points make attractive a MgB2 based SMES system. This is the solution proposed by ASG Superconductors within the V-ACCESS project.

Until now SMES prototypes have been tested in laboratory in on-ground conditions and not in on board or maritime environments that will be carried out within V-ACCESS project. In addition to an on-ground system, the mains additional requests are to be able to accommodate the mechanical movements, vibrations and the maritime chemical atmosphere (moisture, salty environment).

Among the different peak power profiles required on board a ship and described in WP1, it has been possible to limit the SMESs' concepts to only three sizes of system that cover a large range of the commercial electrical ships' requirements identified in V-ACCESS.

The first one stores an energy of 750 kJ (0.21 kWh) corresponding within V-ACCESS to the electrical ferry case. It is considered in this report as a large size power source. The second one stores an energy level of 350kJ (0.1 kWh) that is envisioned within V-ACCESS OSV and only 85 kJ (0.024 kwh) for Trawler. This last design also corresponds to the demonstrator that will be tested within V-ACCESS on the land platform. They are considered below as medium and small size power sources respectively. Beyond their obviously different power profiles that must be tested according to the ship cases, the difference between the three systems is mostly a slight reduction of footprint and weight that remain large (in comparison to supercapacitors) due mostly to the cryostats and auxiliaries required to maintain the cryogenic temperature. It does not significantly modify the acceptance process of on board a ship such as marinization as well as safety, maintenance or general operation procedures. Only the bill of material is different that can slightly impact the cost (COGS), for the other points discussed here such as the supply chain, the manpower skill, the sovereignty can be considered identical for the envisioned systems in this report.

Readiness Level of Supercapacitors for Vessels (TRL)

Current Technology Maturity

Advancements in energy storage systems (ESS) have led to significant improvements in energy density, power density, and cycle life. Technologies like lithium-ion batteries and even supercapacitors have become widely used across various industries, making it a trend to integrate larger-scale ESS on vessels. Energy storage systems can improve power system dynamics and stability. For instance, to meet power or spinning reserve requirements set by class societies, generators often do not operate at maximum efficiency, reducing overall vessel efficiency. ESS can act as power or spinning reserves, enabling generators to run at optimum loads with ESS available to handle 'spinning' reserve duties. This is true also for other emerging technologies such as SMES.

Supercapacitors, like batteries, are based on electrochemical cells containing two conductor electrodes, an electrolyte, and a porous membrane through which ions pass. Supercapacitors store energy by attracting solvated ions to a conducting surface using electric fields. The technology under evaluation is based on Electrochemical Double-Layer, and the type of device is called EDLC or Electrochemical Double Layer Capacitor. EDLCs store energy by separating positive and negative charges across an electrolyte in the order of 0.3–0.8 nm, much smaller than conventional capacitors. EDLCs typically have higher capacitance values but lower voltage limits compared to other types of capacitors. They have a high energy storage capacity, helping bridge the performance gap between fuel cells and batteries. Supercapacitor technologies are ideal for systems requiring a fast response due to their ability to discharge stored energy within milliseconds. They offer higher power capability than most batteries (more than tenfold) and can operate across a wide temperature range.

Due to their physical energy storage mechanism, supercapacitors can be charged and discharged within less than a second for over 1,000,000 cycles, even at temperatures ranging from -40°C to +65°C. This is because they are not limited by the velocity of chemical reactions typical of batteries and the degradation of materials. However, classic supercapacitors are limited in their energy density due to their reliance on surface area for energy storage. New materials, such as Skeleton Technologies' Curved Graphene, offer a larger available surface area, microporosity, and electric conductivity than activated carbons. This increases the energy density to over 10 Wh/kg while maintaining power densities above 30 kW/kg, approximately 100 times higher than lithium-ion batteries. This makes them ideal for applications requiring a quick response with power peaks, such as power quality and peak-power shaving applications. Round-trip efficiencies are also higher than lithium-ion batteries, averaging around 95%, primarily due to very low equivalent series resistance (ESR). Other important characteristics include low maintenance, as they are essentially static systems, and high safety with no risk of thermal runaway, reducing the risk of toxic fumes. Additionally, the materials used in their construction are abundant and have a low carbon emission footprint in the supply chain.

Since the voltage of supercapacitors changes significantly during charge or discharge, a power converter is always needed to match the supercapacitor output voltage with the voltage of the power system. The topologies of power converters used for supercapacitor energy storage systems include buck converters, boost converters, buck-boost converters, and dual active bridge converters. These converters are voltage-source because supercapacitors electrically behave like capacitors and are current-controlled when connected to the shipboard power system.

Integration with Marine Systems

Integrating energy storage systems (ESS) into marine vessels can offer significant benefits to the overall power system, such as providing support to mitigate blackout events, increasing heavy pulsed load capability, improving the propulsion system dynamics, and enhancing the efficiency of diesel generators. Each type of energy storage technology has unique characteristics and trade-offs:

- **Lithium-ion Batteries (LiBs)**: They have a higher energy density and are a more mature technology but may suffer from thermal runaway issues, that raise the safety requirements.
- **Nickel Zinc Batteries**: These have better fault tolerance and higher safety levels but lower maturity and decreased cycle life.

- **Supercapacitors**: They offer much higher cycle life and power density but are limited by low energy density, which restricts their functionality.
- **SMES**: These systems are robust, reliable and with long lifetime, but acquire a sophisticated cooling system and have even less energy content per square meter than supercapacitors.

Comparison of Energy Storage Systems Considering Marine Systems

The table below provides a comparison of various energy storage systems (ESS) for marine applications, highlighting their key attributes:

Table 1 A comparison of various energy storage systems (ESS) for marine applications, highlighting their key attributes

Technology	Energy Density (Wh/kg)	Power Density (kW/kg)	Cycle Life	Safety	Maturity
Lithium-ion	150-250	0.25-1.0	1000-2000	Risk of thermal runaway	Mature
Nickel Zinc	70-100	0.3-0.8	500-1000	Higher safety, good fault tolerance	Emerging
Supercapacitors	4-10	10-30	>1,000,000	No thermal runaway	Mature, but not in marine
SMES	0.206	0.350	Not limited to	No thermal issues as it is actively cryogenically cooled	Emerging

Supercapacitors vs. Superconducting Magnetic Energy Storage (SMES)

- **Supercapacitors** and **Superconducting Magnetic Energy Storage (SMES)** have similar characteristics in terms of energy density.
- **Power Density**: Both Supercapacitors and SMES are suitable for applications requiring high power for short-term energy delivery, with similar power density.
- **Lifespan**: Both have a lifespan much longer than batteries.
- **Reliability and Maintenance**: SMES need several auxiliary systems, reducing reliability and increasing maintenance costs. Supercapacitors are simpler but might require forced air or liquid cooling in confined spaces, bringing their maintenance needs closer to those of SMES.
- **Design and Modularity**: Supercapacitors are based on low-voltage, low-energy cells, requiring many cells in series and several strings in parallel to achieve the necessary voltage and power levels. SMES

typically involves a bespoke design for a single coil tailored to specific voltage and power requirements, potentially offering weight and volume advantages for vessel power levels. However, SMES lack the modularity of Supercapacitors and LiBs.

- **Electromagnetic Interference (EMI)**: Supercapacitors and LiBs do not have significant issues with EMI as they accumulate energy in electric fields at low voltage. However, SMES, designed with a single coil, can generate intense magnetic fields that must meet limits on maximum public exposure.
- **Safety**: Supercapacitors share similar risks with batteries regarding flammable electrolytes and potential leaks but are not prone to thermal runaway. SMES risks include leaks of cryogenic liquid, though this can be mitigated with direct cooling.

Market Demand

Market Readiness and Application

The shipping industry is exploring fossil fuel alternatives. Pure battery-driven vessels are currently feasible only for small-scale implementations like ferries and boats. However, hybrid systems combining chemical and electrochemical storage allow the battery system to stay active at low loads, while combustion engines mainly cover marine propulsion.

Currently, surface navy vessels primarily use ESS as uninterruptible power supplies for critical equipment such as essential auxiliary services, navigation, or communication systems, where the required energy and power are typically low. However, the existing vessel power systems may not be designed to maintain power quality due to the evolution of advanced mission systems like directed energy weapons or stochastic electronic warfare systems. Electrical inertia may not withstand high pulsed load demands with high power ramp rates, causing excessive heating and mechanical stress to the generator and adversely affect connected loads. Integrating ESS can smooth power perturbation from pulsed or dynamic loads, reducing generator stress and improving power distribution network quality.

Different ship types have unique power demands and operational profiles, which significantly influence the feasibility and economic benefits of ESS integration. The role and impact of electrical storage system vary depending on whether the vessel is designed for short sea shipping, offshore support, or deep-sea voyages. Consequently, vessel-specific studies are essential to determine the most suitable ESS solutions and to optimize cost-benefit outcomes. Examples below are Ferries, OSVs, Cruise Vessels, Offshore Drilling Units, Fishing Vessels, Fish Farming Vessels, Shuttle Tankers and Short Sea Shipping.

TABLE 2. ECONOMIC FEASIBILITY OF ELECTRIFICATION

	Savings Potential	**Payback Time**
Ferries	All-electric ferries can achieve significant fuel savings, though the cost of electricity and maintenance must be factored in.	A 2015 study by Siemens and Bellona found that converting 70% of Norwegian ferries to battery or hybrid systems would result in a payback period of approximately 5 years. Given recent advancements in battery technology and cost reductions,

		payback times could now range from 1 to 6 years
OSV	OSVs using ESS for dynamic positioning (DP) and as a spinning reserve can realize fuel savings of 5-20%.	Studies suggest a payback period of 2-5 years, which is expected to decrease as technology matures and costs fall.
Cruise Vessels	The integration of batteries in cruise ships can reduce the number of diesel engines needed, especially during maneuvers. This not only saves fuel but also reduces maintenance costs.	Highly variable depending on the operational profile and configuration. In some cases, batteries serve as a "ticket to trade" in environmentally sensitive areas, making them essential for operation rather than purely for economic savings.
Offshore Drilling Units	Offshore drilling units can achieve significant reductions in engine running hours by using ESS for dynamic positioning and peak shaving, potentially saving 10-15% on fuel.	Payback periods can be as short as 1-3 years, particularly when the system is optimized for closed bus operations, which further enhances efficiency.
Fishing Vessels	Fishing vessels can benefit from reduced operational costs and lower idle running times by integrating batteries. Depending on the type of operation, batteries can cover entire fishing operations.	Estimated payback periods range from 3-6 years for typical fishing vessels, though this can vary based on the vessel size and operational characteristics.
Fish Farming Vessels	Fish farming vessels, particularly feeder barges and service vessels, can achieve significant savings by optimizing engine use with ESS.	Typically ranges from 3-7 years, depending on vessel type and operational location.
Shuttle Tankers	Shuttle tankers can benefit from ESS by removing generators during cargo operations and optimizing overall energy use, leading to energy savings of up to 32%.	Varies from 1-5 years, heavily influenced by the vessel's design and operational profile.
Short Sea Shipping	ESS can be particularly beneficial for vessels requiring frequent maneuvering or operating in zero-emission zones.	It can range from immediate to indefinite, depending on whether the technology is used for operational efficiency, safety, or regulatory compliance.

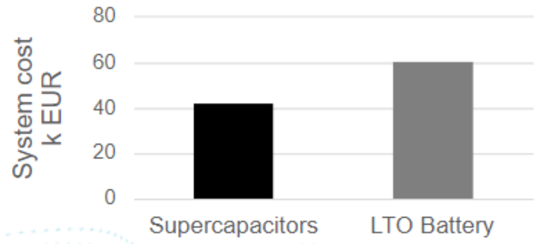
The cost-effectiveness of integrating ESS into maritime applications is influenced by several factors, including the vessel's operational profile, the type of ESS used, and the specific technological requirements.

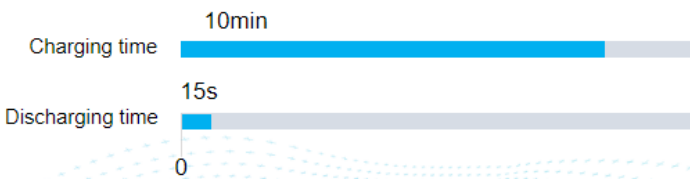
- **C-rate and Cycles:** Different ship types demand varying C-rates (charge/discharge rates) and cycle lifetimes from their ESS. Ferries and offshore vessels typically require very high C-rates, while deep-sea vessels have highly variable requirements.
- **Energy Density:** High energy density is crucial for applications where space is limited, such as tugboats and high-speed ferries. Lower energy density solutions may suffice for vessels with more space or less stringent energy demands.
- **Technology Selection:** The choice between NMC (Nickel Manganese Cobalt), LFP (Lithium Iron Phosphate), LTO (Lithium Titanate Oxide), or supercapacitors depends on the specific operational needs and cost considerations. NMC is preferred for high-energy applications, while LTO and supercapacitors offer advantages in high-power, low-energy scenarios.

Use cases analyzed for high-power short term energy storage

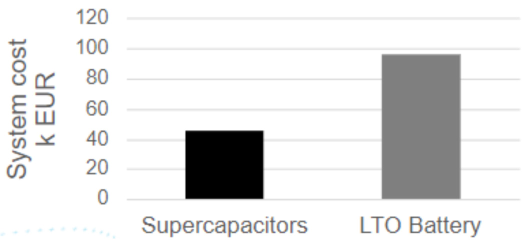
The following section lists all possible use cases where hybrid storage or short-term energy systems could be economically and technically feasible in the marine sector. Whether it is supercapacitors or SMES, the principle remains similar. Use cases chosen below typically require both high charge rates and a high number of cycles making these a good fit for applications for supercapacitors and SMES. For the sake of simplicity, the comparison below is made between supercapacitors and lithium-titanate batteries (LTOs). The LTO Technology chosen is already technically and economically a very good fit as they have higher C-rates and power capabilities compared to other LiB chemistries. Price comparison is based on system size (kWh and available C-rate) and average cost per kWh of LTO, which indicatively chosen to be 1200 €/kWh. Supercapacitor system size can be small in comparison, as it enables C-rates from a few hundred to thousands. Price per Wh for supercapacitors on average is 20 €, and for active heave compensation system it means less than 2kWh system is needed compared to 100 kWh for LTO.

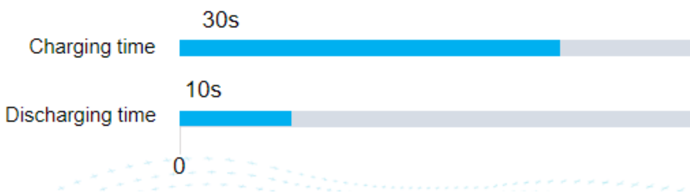
- **Back-up Power**: Critical equipment onboard marine vessels cannot be left without power, even for short periods. A back-up system is mandatory to ride through short power outages without effects or, in the case of long outages, to safely shut down equipment in a manner that allows for the easiest restoration of operations. For this application, a high-energy density is desirable to reduce the space needed for the back-up power supply and provide a fast response.





- **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 stress the generators and accelerate their wear. 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, requiring a charge/discharge cycle of 1-20 seconds with many cycles per day.

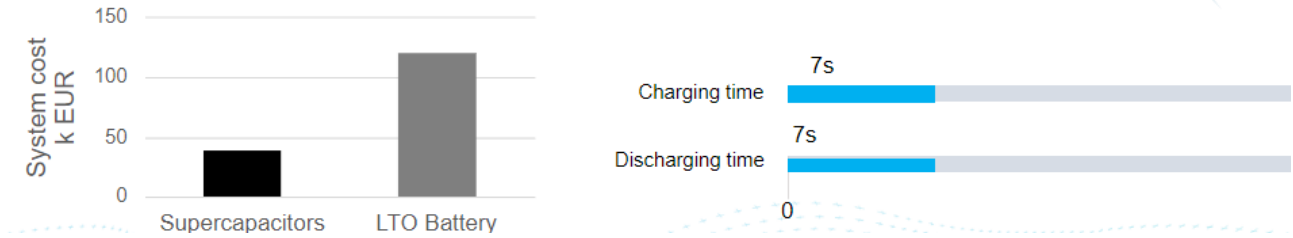




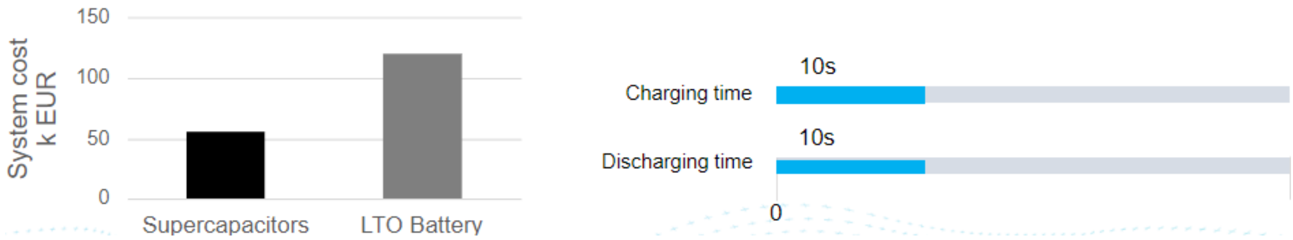
Using supercapacitors for power support of the 1-20s is the best idea since it allows minimize the footprint of the energy storage system, their high robustness does not cause safety risks (typical of

Li-on batteries), and they can accept both positive and negative loads without significant effect on aging.

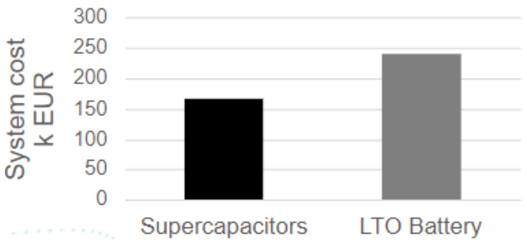
- **Active Heave Compensation (AHC)**: AHC, which is also one of the use cases analyzed in V-ACCESS project involves the precise control of the vertical position of some payload (e.g., a pump or a drill) held by a crane, even in the presence of waves and wind. This periodic movement is characterized by short power cycles of high peak power consumption and regeneration, which can stress the vessel power system. Supercapacitors can store energy during heave-up movements, which is then discharged when needed, reducing peak energy load on ships' main power systems and increasing system efficiency. AHC use case shows one of the best fits for short-term energy storage systems due to its specifically short application time and frequency. This implies also for SMES.

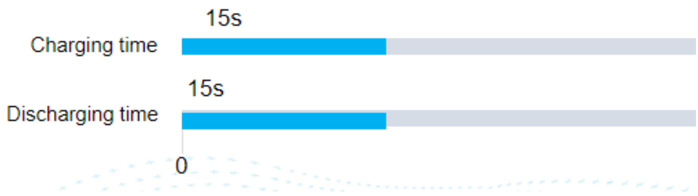


- **Motion Compensation**: Similar to AHC, pile gripper ships and other offshore vessels require holding a load in a still position (e.g., a wind turbine mast being planted in the sea bottom). Without compensating for the horizontal movement of the vessel, this task would be impossible. Electric drives normally control movement, which requires high peak power. Energy storage allows to reduce the sizing of the generators while allowing them to work more smoothly, saving fuel and increasing the engines' life expectancy.

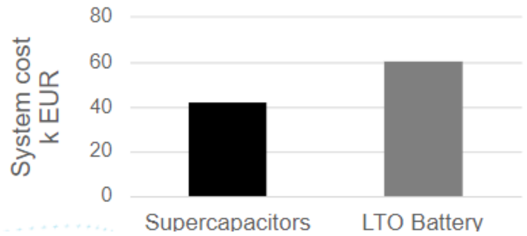


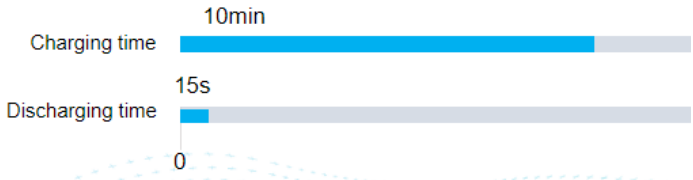
- **Parallel Hybrid Propulsion**: Ships operating in adverse sea conditions experience fluctuating loads on the propellers and shafts due to the waves. The size of the ship compared to the waves influences the overall effect, but fuel consumption during cruising and maneuvering increases by up to 20% compared to calm water conditions. Adopting energy storage can enable fuel savings of up to 20% and longer engine lifetime.



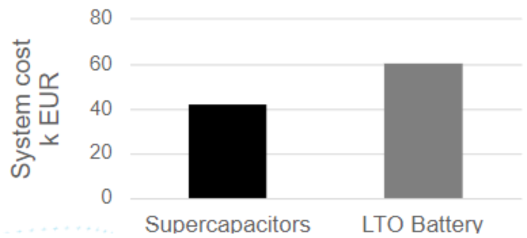


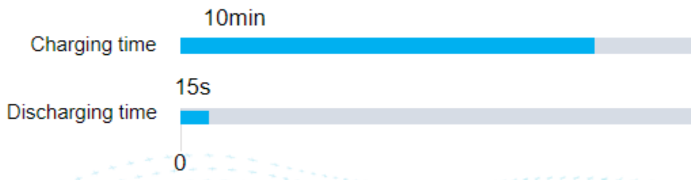
- **Engine Gradient Support**: Marine vessels, especially in Oil & Gas and offshore operations, are equipped with pumps and other highly discontinuous loads, generating step loads on the power distribution, which can cause genset instability, especially when cleaner fuels such as LNG are used. Fast-reacting energy storage can enhance slow-responding gas engines, increasing the stability of the power system and reducing fuel consumption due to smoother genset operation.



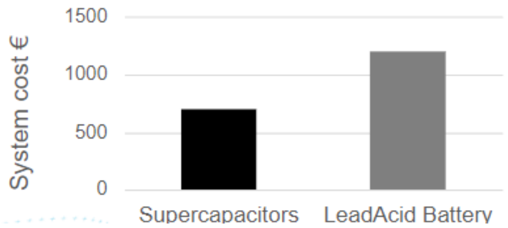


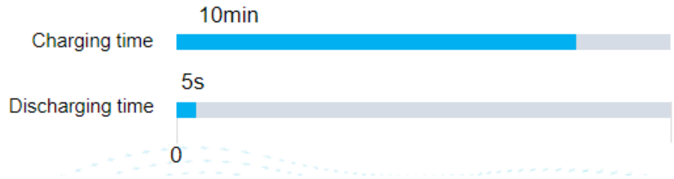
- **Floating Cranes**: Floating cranes operate in harbors, serving various purposes, including material handling, engineering works, bridge-building, and port construction. They run on diesel generators, but these are extremely oversized to handle highly variable loads, causing high fuel consumption. Energy storage allows recovering energy during the lowering of the load, instead of dissipating it by a brake. For this application, energy storage needs to operate with short cycles and large amounts of energy, with cycles repeated many times per day.





- **Engine Start**: Generators, using diesel or increasingly natural gas, are the main power sources 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.





To illustrate the fact that short-term energy storage systems are viable in niche marine applications the *Ar Vag Tredan* is the world's first electric ferry powered entirely by supercapacitors, conducting 28 crossings per day with a charge time of 4 minutes and a journey time of 7 minutes. The supercapacitors are expected to last 15-20 years, showcasing their potential in diverse marine duty cycles as more boats convert to electrical power. If the power profile requires more energy content, then also combined hybrid systems with larger batteries could be an option. In some cases, it is possible that current lithium NMC/iron phosphate chemistries used in batteries can produce enough power independently as well, but if the available size is essential, not to over dimension batteries for high-power dynamic loads, then supercapacitor/or-SMES/battery hybrids could potentially become popular in the future.

Go-to-Market Strategy

The existing fleet of hybrid ferries, workboats, tugs, and offshore vessels have consistently demonstrated 15-30% fuel savings over comparable diesel boats. For large merchant vessels powered by very large two-stroke engines using direct drive, the gains from hybrid power systems are minimal as they operate their engines close to the optimum load for long periods with little fluctuation. However, even these vessels may benefit from a relatively small battery for improved load management. Hybrid propulsion is expected to become the norm for all boats that cannot be fully battery-electric, with a typical payoff period of less than ten years. Regardless of future fuels used to decarbonize shipping, hybrids will play a role as diesel engines, fuel cells, and combined cycle gas turbines all experience efficiency losses when operating at partial loads.

High energy batteries vs high power storage systems

Mature battery technologies in Marine

Lithium-ion batteries are currently characterized mainly by their cathode choice, with nickel manganese cobalt (NMC) being the most popular in marine and automotive applications due to its reasonable safety and very good cell-specific energy. However, NMC has issues with thermal stability and depends on cobalt, which is scarce, expensive, and has ethical supply chain issues. NMC batteries use flammable organic electrolytes and are vulnerable to thermal runaway, requiring extensive fire extinguishing systems and continuous cooling in marine applications. These safety measures significantly reduce the installed energy density of marine NMC battery packs compared to automotive packs (e.g., 86 Wh/kg for the Ellen E-ferry vs. 160 Wh/kg for a Tesla Model 3).

Lithium iron phosphate (LFP) batteries, with about 65% of the specific energy of NMC but much safer and free from cobalt and nickel issues, present a viable alternative. The increased safety of LFP batteries may allow their specific energy in marine applications to approach that of NMC batteries. With wider adoption, the price of LFP batteries should drop significantly below that of NMC.

Currently, lithium NMC technology allows battery-electric boats to achieve a range of up to about 50 km. With the advent of solid-state batteries, this range could triple to 150 km in about ten years. Lithium-air batteries might further double this range to 300 km, indicating that battery-electric boats are unlikely to significantly exceed a 500 km range and will probably never sail further than 1000 km. For longer journeys, a hybrid solution will be required.

The diverse energy storage needs of marine vessels call for a range of solutions, from lithium-ion and lithium-iron phosphate batteries to advanced solid-state and lithium-air technologies. As battery technology continues to evolve, hybrid systems combining various energy storage methods will be essential to optimizing performance, efficiency, and safety in marine applications.

Value Proposition from supercapacitors or SMES

In maritime applications, high power energy storage systems such as SMES or supercapacitors are particularly suitable for peak shaving, where they are constantly charged and discharged. The need for storage of the absorbed energy is limited. For example, they can be used to absorb loads from heave compensation of cranes. Some of the advantages are having a high specific power, safety and for supercapacitors specifically, it is also commercially available on the market.

Even though full electrification will only be applied in waterborne transport segments that have shorter and/or fixed/predictable routes, hybrid solutions play a crucial role in optimizing energy management for certain processes on board a vessel. New technologies might require additional energy storage systems such as supercapacitors or SMES to cover fluctuating load variations and increase the efficiency, reliability, and flexibility of the entire power system. A significant advantage of fully electric drive is high energy efficiency, with minimal thermal loss of energy—around 5-10% compared to 50-60% energy loss in internal combustion engines and fuel cells. Especially in situations with a shortage of green electricity, the option of full electric propulsion system charged from the grid is very attractive. These electric technologies can also be used for peak shaving and stabilizing the electricity grid, given the expected increase in fluctuations due to more electricity coming from renewable sources such as wind, water, and solar power.

The full electric option should be developed and deployed as much as possible for vessels that can recharge frequently or swiftly exchange swappable energy storage units (short distances and/or fixed routes and timetables). With increased technological performance, particularly for supercapacitors and electric drivetrains, fully electric propulsion can become a viable option for some inland waterway transport (IWT) segments in the short term, and potentially for all IWT in the long term, depending on land-side infrastructure (e.g., high-capacity recharging facilities and battery swapping terminals along waterways and in ports).

Given the current and foreseen developments for both fully electric and sustainable alternative fuels, the hybrid option may be relatively inefficient. However, the ultimate decision should be based on an in-depth analysis of the operational profile, the layout of a specific vessel (e.g., fuel storage options), and the available power/fuel sources in the region and their price levels. As expected, the uptake of hybrid solutions is rising steadily, with a faster pace than fully electric options. For example, the ferry fleet and offshore fleet (offshore supply vessels) are the types most opting for hybrid solutions.

Challenges for Scale-Up Market

Scale-up challenges

In the context of scaling up novel energy storage technology for marine applications, several challenges and market dynamics must be considered, even when supply chains are secured, and costs are significantly reduced.

1. Technological Integration:
    - Compatibility with Existing Systems: Integrating supercapacitors/SMES into existing marine power systems can be complex. They must work seamlessly with other energy storage technologies, such as batteries and fuel cells, to optimize performance.
    - Performance Under Marine Conditions: New technology must demonstrate reliability and efficiency in harsh marine environments, including varying temperatures and humidity levels.
2. Regulatory Compliance:
    - Environmental Regulations: The marine industry is subject to stringent environmental regulations, which may impact on the design and implementation of new energy storage solutions. Compliance with these regulations is essential for market acceptance.
    - Safety Standards: Ensuring that supercapacitor systems meet safety standards is critical, especially in applications involving high power outputs and energy density.
3. Market Acceptance and Adoption:
    - Skepticism Towards New Technologies: The marine sector traditionally relies on established technologies. Convincing stakeholders to adopt supercapacitors/SMES requires demonstrating clear advantages over existing solutions.
    - Cost vs. Performance Trade-offs: While COGS may decrease with mass production, the initial investment in supercapacitor/SMES technology could still be perceived as high compared to conventional systems.
4. Supply Chain Resilience:
    - Material Sourcing: Even with secured supply chains, fluctuations in the availability of or price of raw materials (e.g., carbon for electrodes) can affect overall production costs.
    - Logistics Management: Efficient logistics are crucial for timely delivery of components, especially in maritime operations where downtime can be costly.

5. Workforce Development:

    - Skilled Labor Shortage: The transition to advanced technologies like supercapacitors requires a workforce skilled in new manufacturing processes and technologies. Training programs will be essential to bridge this gap, which is also part of the V-ACCESS project.

    - Retention of Qualified Personnel: As demand for skilled workers increases, retaining talent becomes a challenge amidst competition from other industries.

Securing supply chains and reducing costs are significant steps toward successful scale-up, also addressing technological integration, regulatory compliance, market acceptance, supply chain resilience, and workforce development will be crucial for the successful deployment of novel technologies in marine applications. The potential benefits of enhanced efficiency and sustainability present compelling reasons to navigate these challenges effectively.

Supply Chain Security

Use of Critical Raw Materials

Typically, supercapacitors are compared with LiB technology due to its similarity in terms of product. Although both consist of positive and negative electrodes, separator and liquid electrolytes forming a metal container, its contents differ a lot. Rare earth and scarce metals are not required for supercapacitors since its electrodes are made of activated carbon on aluminum foil for both electrodes. V-ACCESS partner Skeleton Technologies has developed and patented its own active carbon material called Curved Graphene, which offers even more sovereignty in context of EU value chain.

For LiB the materials needed, although dependent on the chemistry used, still include lithium and for high energy content typically also cobalt and nickel. It can be argued that the mining and refining phase of the battery life cycle with nowadays technologies has lower environmental impact compared to fossil fuel-based systems. Still, the choice of materials for electrodes and electrolytes is crucial as the environmental impact depends on the materials used. For example, mining some electrode materials increases the environmental footprint due to toxic substances leaking from mining tailings.

More popular LFPs contain lithium but avoid nickel and cobalt, resulting in an estimated 22% lower toxic impact compared to standard lithium-ion batteries (NMC111). However, other environmental impacts may not improve, and overall, these batteries may not be more environmentally friendly.

Details regarding the supply and mining of some main components used in NMC batteries (the volume leaders in the maritime industry) include:

- **Cobalt**: Adds stability and energy density to lithium-ion batteries but increases volume and cost. Over 60% of the world's cobalt is mined in the Democratic Republic of Congo, which has significant political and ethical issues. Several initiatives are ongoing for responsible cobalt mining.

- **Nickel**: An important and relatively expensive component, widely used in stainless steel production. Market fluctuations can affect its price. The market is well developed.

- **Lithium**: While supplies are significant, only one-third is economically accessible, primarily from salty, briny lakes. The evaporation process is lengthy. Total availability from underutilized sources in Chile, China, and Australia appears reliable long-term.

The demand for batteries will increase pressure on material resources, presenting issues such as resource availability, toxicity, safety, and impacts of production and recycling or disposal. This is likely to correspond to an increase in raw material prices. This is why short-term energy storage systems that do not rely on critical raw elements can rise to attention, because electrification process continues for cleaner environment.

SMES material analysis

There is no standardized SMES production for use cases under evaluation of V-ACCESS. SMES parts are manufactured within ASG superconductors and/or separately purchased on the market such as the cold heads and its compressors the cryostat, the converters. Still subcomponents integration in the system has already been demonstrated for many superconducting magnets. These components can be purchased in EU even if today some elements are from the USA or Japan for cost or availability. The SMES cryostats are built with common cryogenic stainless steel (EN 10088-2), and coil mandrel and mechanical support are made our Glass Fibre reinforced Resin (GFR) that can be provided by several steel or GFR European producers.

Regarding to MgB_2 wires, these are made out for metallic Mg, B, Ni and Cu alloys (Monel). It required approximately 10 km for a 750 kJ SMES with respectively 5kg for Mg and B, 40 kg for Ni and 65 kg for Monel.

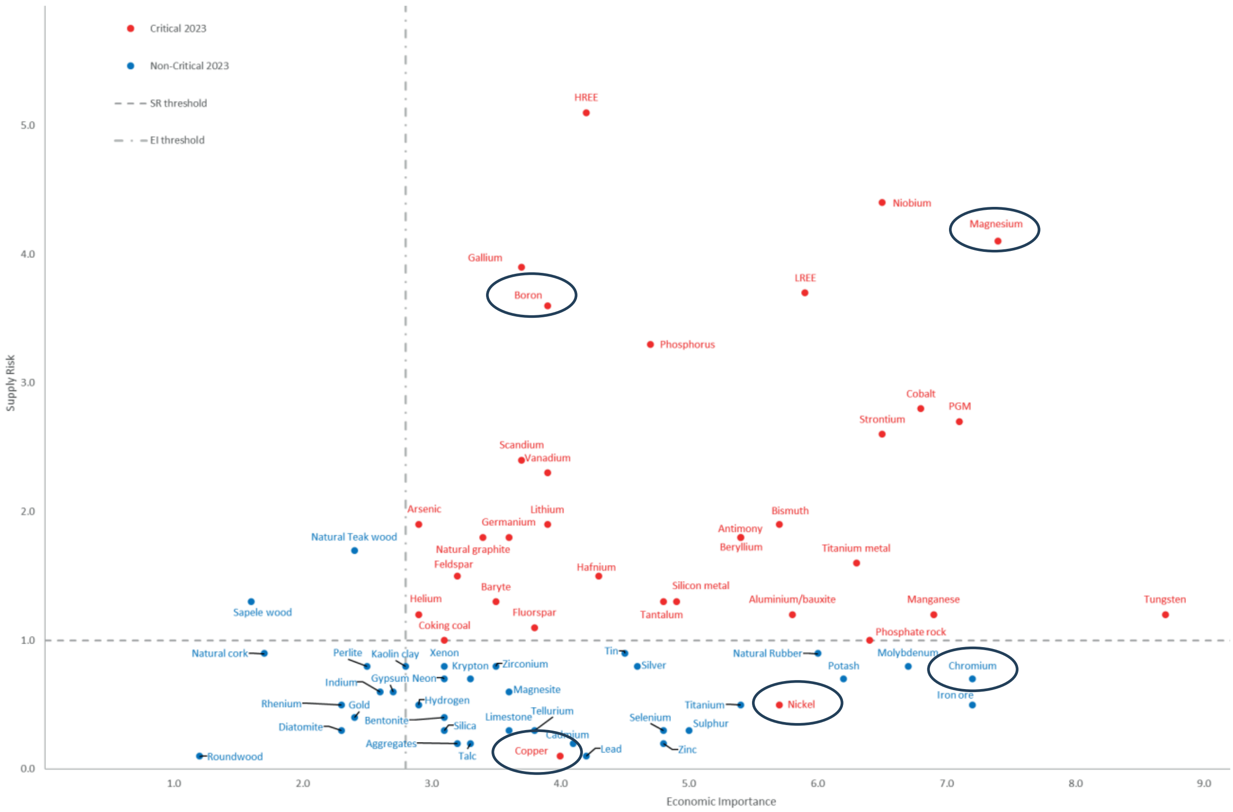


FIGURE 1 CRITICAL ASSESSMENT RESULTS OF RAW MATERIALS (2023) [5]

As Figure 1 shows, magnesium (Mg) and boron (B) are considered critical raw materials for Europe, while nickel (Ni), copper (Cu) and chromium (Cr), stainless steel (SS) EN 10088-2 and Monel are below the defined critical threshold but are considered of concern for the future.

Copper has recently entered the list. As its supply is very diversified, it was not considered critical. Nowadays it is more and more difficult to replace this metal, because of its superior performance as part of the massive trend towards electrification of the world. However, its use in superconducting wires as a matrix considerably reduces its necessity and could provide a substitute. Nickel, a key element in batteries, is recently regarded as critical. In the previous analysis, it was not considered critical due to the good diversification of supply over the period under review. This change in classification reflects the concentration of ownership of production capacity, or private contractual agreements, which could become a problem in the future for massive use in batteries. Today, in Europe, it is mainly imported (29%) [5] from Russia.

Beside their criticality, the quantity of SS, Ni, Cu and Monel (CuNi) alloys required for the SMES manufacturing is very limited in comparison to the European uses and productions. Many metal producers can provide the required cryostat.

Magnesium:

Magnesium is used in Europe mostly used in lightweight alloys for automotive, electronics, packaging or construction and as a desulphurisation agent in steelmaking. It is massively imported from China (97%) to EU [5]. The trend is towards recycling with 12% in EU. In MgB_2 wires it is used as fine metallic powder. The world production is nearly 1000 million ton per year. The quantity need for SMES is however very limited 5kg per 750 kJ system, which is negligible regarding the world production.

Boron (borate B_2O_3):

It is growing market supported by the renewable energy market (permanent market for wind mill or component for glass in solar panel. In EU, resource nearly uniquely comes from Turkey (99%) [5], but can be also extracted in North and South America. There is not yet a recycling industry for this material. The world production is over 3.5 million tons per year of borate. Due to a limited demand, only a little among of borate is transformed to the boron metal required for the MgB_2 wires. However again, the quantity need is 5kg per 750 kJ SMES which is negligible regarding the world production.

Supply Chain Constraints and Issues

Any discussion regarding the use of electrical storage systems on boats must consider alternative fuels. Even energy dense batteries are unlikely to store all the energy required for journeys longer than 500-1000 km. While battery technology remains relevant for longer journeys as part of hybrid propulsion systems, there remains a pressing need to replace the large consumption of bunker fuel with alternatives that are less carbon-intensive and eventually carbon-neutral. This need is critical given that the proportion of boats that could potentially be fully electric is very small relative to global shipping. Heavy fuel oil constitutes 77% of total marine fuel use, and 90% of marine fuel is consumed by cargo-carrying ships; only 10% is used by passenger ships, fishing boats, tugboats, navies, and others. Although some cargo-carrying ships with shorter journeys could transition to electric systems, most cargo ships cannot. Energy-dense battery technology alone cannot solve this challenge and reliable, robust and modular short-term high-power energy storage systems that support batteries during dynamic loads, are good fit. It would give more longevity for the battery packs and avoid over dimensioning the system for the sake of power need.

Bottlenecks

One of the main bottlenecks of electrification in the marine sector is the dependence on lithium in the electrolyte and electrode components of Lithium-ion batteries. This puts pressure on the lithium supply chain, especially because the electrification process is ongoing in all areas of the transport and not only, also grid storage sector and other industrial sectors move towards it in EU.

Additionally, specific power requirements that for example wave compensation systems need to stabilize cranes and other devices against ship movement in waves. Power is required when the ship descends, and energy can be recuperated when the ship ascends. Typically, this energy is either lost as heat or stored in batteries, which are less efficient and have shorter lifespans compared to supercapacitors or other short-term high-power energy storage systems. Currently, marine-certified supercapacitors have been unavailable due to high development and certification costs relative to market potential. This demonstrates a weaker risk/reward ratio compared to other domains such as automotive, public transport, or warehouse logistics.

A typical wave heave compensation system operates for about 4 hours daily, encountering a wave every 6 seconds, totaling over 800,000 waves annually. Each year, more than 1 GW of Active Wave Heave Compensation Systems are installed, emitting nearly half a million tons of CO_2, unless energy is recuperated during the opposite phase of the wave. Theoretically, energy recuperation could be complete if waves were identical, but practical inefficiencies in electric motors and energy storage result in energy losses.

Currently, there are a few experimental supercapacitor-based wave heave compensation systems. While these pilot projects have shown success, the main issue is compliance. There are no marine-certified supercapacitors systems, as regulatory updates demand specific certification for marine use.

For supply chain bottlenecks not many challenges are identified, because as was described in the sections above, all materials used for technologies under evaluation (SMES and supercapacitors) are available in the EU market. Of course there are some uncertainties with Mg, and B as well as some specific carbon materials coming outside of EU, but these are mitigated for example by companies own material engineering efforts.

Market Entry Potential and Barriers for Supercapacitors in the Marine Segment

Market Acceptance

The marine industry is adopting stringent fuel efficiency norms that drive the electrification and hybridization of systems. Supercapacitors and SMES can be used in peak load-shaving applications to supply power and allow generators to operate at constant loads while absorbing excess generated power. They could also be utilized in active heave compensation to mitigate the impact of waves on offshore vessels and platforms, absorbing excess power generated by cranes on ships and at ports as described in previous sections of this report.

Increased high-power storage solution adoption is anticipated for capturing waves and offshore renewable energy. Their safety advantages over batteries, such as a lower risk of fires, contribute to their attractiveness in marine applications as well.

The integration of ESS into maritime applications offers several economic benefits beyond fuel savings and reduced emissions, which improves market acceptance. These include:

- **Enhanced Operational Flexibility:** Hybrid and all-electric systems enable more precise control over power usage, improving the vessel's ability to adapt to varying operational demands.
- **Reduced Maintenance Costs:** Fewer engine running hours and optimized load management lead to lower maintenance costs and longer intervals between overhauls.
- **Regulatory Compliance and Market Access:** As environmental regulations become stricter, ESS integration can serve as a "ticket to trade" in markets that require low or zero emissions, such as within Emission Control Areas (ECAs).

Integrating ESS into maritime applications offers a compelling economic proposition, particularly as electrical storage technologies continue to advance, and costs decrease. While payback periods and savings potentials vary across vessel types and operational profiles, the broader trend indicates significant opportunities for cost reduction and operational improvement. The strategic selection and integration of ESS, tailored to specific vessel needs, are key to maximizing these benefits and achieving long-term economic sustainability in the maritime industry.

Importance of Sovereignty

Electrical power is essential for various marine applications, including sailboats, yachts, tanker ships, and offshore vessels, which transport people and cargo over significant distances. Marine vessels, due to their size, weight, and operational scale, have high power requirements, leading to increased environmental impacts. The maritime sector contributes significantly to global emissions; for instance, cruise ships emitted more sulfur oxides (SO_x) in 2017 than all cars in Europe.

Increased electrification is an effective strategy to reduce maritime emissions. Leading marine vessel manufacturers are replacing combustion and hydraulic systems with electrical energy storage. While batteries are commonly used in power management units on sea vessels, supercapacitors offer advantages in specific cases. Batteries face limitations such as short lifespan, difficulty in engine starting, and risk of thermal runaway due to high operating temperatures. Supercapacitors, in contrast, provide stable, power-efficient solutions with millions of charge/discharge cycles, potentially lasting up to 20 years under optimal conditions. The same arguments can also be listed about SMES. They perform well across a wide range of operating temperatures, including cold conditions, which is beneficial compared to batteries and are advantageous for reliable engine starting in marine vessels.

To reduce in-harbor pollution, harbor operators offer incentives for vessels to use electrical power during maneuvering and provide shore-to-ship power options to charge batteries and power ships while docking. Hybrid electric-powered vessels typically require:

- **High Power for Disembarking and Maneuvering:** 50-100% power for durations up to 5 minutes.
- **Mid Power for Acceleration:** Usually around 50% of maximum power.
- **Low Power for Cruising:** Typically, around 20% of maximum power for extended periods, using downsized combustion engines.
- **High Power for Maneuvering and Braking:** Full throttle peaks for periods of about 5 minutes.

High-power maneuvering and braking events put significant stress on batteries, leading to reduced lifespan and autonomy with a single charge.

Depending on the vessel's distance coverage, either fully electric or hybrid solutions may be implemented. Fully electric systems are common for city cruisers or taxi boats, while hybrids are suitable for longer distances. Key observations include:

1. **Cruising Power:** About 20% of full power needed, allowing significant reduction in diesel generator size, which contributes to reduced pollution.
2. **Maneuvering Power:** Significant power required for short durations, often leading to oversized battery banks handling peak demands.

Supercapacitors and SMES can help resolve battery challenges in two ways:

1. **Improving Power Density:** They offer high power density, ideal for handling peak power requirements during maneuvering, reducing the need for oversized battery banks.
2. **Extending Battery Life and Runtime:** High power demands, even for brief periods, can significantly reduce battery range and accelerate wear. They can absorb these high-power pulses, protecting batteries and extending their lifespan.

Regulations

Shipping operates under international environmental, security, and safety standards established by the International Maritime Organization (IMO), a United Nations agency responsible for drafting, discussing, approving, publishing, and maintaining these regulatory instruments. Key international regulations include:

- **Prevention of Air Pollution from Ships**
- **International Convention for the Safety of Life at Sea (SOLAS)**
- **Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments**
- **International Maritime Dangerous Goods Code**

DNV class rules cover the use of batteries in vessels, whether through hybrid solutions or fully battery-driven vessels. DNV GL published initial rules for lithium-ion batteries in 2012, with updates in October 2015 and the latest edition in January 2018, amended in July 2018. These rules focus on the safety of battery installations and specific test requirements. The Class rules for battery notations include:

Battery (Safety)

- Mandatory for all DNV classed vessels with an aggregate battery capacity exceeding 20 kWh.
- Covers safety requirements for battery installations, including vessel arrangement, environmental control, fire integrity, detection, and extinguishing measures.

Battery (Power)

- Mandatory for vessels where batteries are used as propulsion power or as a redundant power source.
- Requires compliance with redundancy and location requirements and calculates the battery's energy supply time or range based on planned operation or voyage.

Similar framework needs yet to be developed for novel emerging technologies such as supercapacitors and SMES and the first steps are being done also during V-ACCESS project. Work done up to this point has shown that several topics can be taken directly from battery rules and applied for supercapacitors and SMES with slight modifications.

Steps to Increase TRL

To implement new technologies such as supercapacitors and SMES on marine vessels for reducing carbon footprint the high maturity level must be achieved. For that a well-thought-out road map for development process is essential to ensure efficient process. TRL framework is one way to assess how far the development is from market launch while allowing them to plan the trajectory to that goal. Each TRL establishes criteria that enables to progressively develop and test a product idea through prototypes and eventually move towards mass-production. Each level of course comes with specific challenges that could hinder progress significantly. The more we move in levels, the more uncertainties there are and therefore specific challenges to be identified. During the V-ACCESS project technologies under evaluation are on different TRLs, therefore the challenges differ. However, if we move up on a scale towards the deployment phase the challenges become more similar.

General aspects of raising TRL in Marine

Various energy storage technologies offer different advantages and limitations in marine applications. Here is an overview of the current state of these technologies and steps to increase their Technology Readiness Level (TRL):

Lithium-Ion Batteries

Strengths:

- Good overall performance: Lithium-ion batteries (LiB) exhibit strong performance characteristics, including high energy density.
- High TRL: Li-ion batteries have achieved a high TRL, indicating their readiness for commercial deployment.

Concerns:

- Thermal runaway: The main concern with Li-ion batteries is the risk of thermal runaway, which can lead to fires or explosions. However, most manufacturers have implemented protection systems to mitigate this risk.

Improvements:

1. Enhance thermal management: Improve cooling systems and thermal insulation to prevent overheating and mitigate thermal runaway risks.
2. Advance Battery Management Systems: Develop more sophisticated battery management systems (BMS) to better monitor and control battery conditions.
3. Rigorous testing: Conduct extensive testing under various operational conditions to ensure safety and reliability.

Supercapacitors

Strengths:

- High cycle life: Supercapacitors offer an exceptionally high cycle life, making them suitable for applications involving frequent charge/discharge cycles.
- High TRL in other sectors: Supercapacitors also have a relatively high TRL, indicating that they are close to full commercialization also in marine.

Limitations:

- Low energy density: The primary limitation of supercapacitors is their low energy density compared to batteries, restricting their use to load leveling applications.
- Compliance in marine: Not achieved and is regarded as novel technology

Improvements:

1. Improve energy density: Research and develop new materials or configurations to enhance the energy density of supercapacitors.
2. Achieve compliance by the certification bodies involved in the marine sector
3. Cost reduction: Focus on reducing the production and material costs to make supercapacitors more economically viable.

SMES

Strengths:

- Safety: are considered a safe option with less risk of thermal runaway.
- Cycle life: The cycle life of SMES high
- High discharge rate: They can handle high discharge rates effectively.

Concerns:

- Low TRL: SMES currently have a low TRL, meaning they are not as mature as other technologies even in other sectors than the marine.

Improvements:

1. Increase TRL through Prototyping: Develop and test prototypes in real-world conditions to gradually increase their TRL.
2. Optimize Performance: Focus on optimizing performance metrics such as energy density and charge/discharge efficiency.

Converter Topologies

Different converter topologies impact the design considerations for integrating energy storage systems (ESS) in marine applications.

- Modulation Exceeding Limits: Pulsed loads can cause voltage and frequency modulation that may exceed STANAG limits (specific operational limits or standards that must be adhered to, such as voltage and frequency modulation).

Recommended Solutions:

1. Deploy ESS: Implement energy storage systems (ESS) to mitigate modulation issues. ESS can reduce voltage and frequency modulation from approximately 3.8% and 1.5% to 0.6% and 0.1%.
2. Delay Output Power: Utilize ESS to delay output power by up to 60ms before exceeding STANAG limits.
3. Optimize ESS Capacity: Determine and optimize the required capacity and size of ESS based on the number of pulsed loads.

To advance the TRL of these technologies, focus on improving safety, performance, and cost-effectiveness while addressing specific application needs. For Li-ion batteries, enhancing thermal management and battery management systems is crucial. Supercapacitors require advancements in energy density and cost reduction. Effective use of ESS can address voltage and frequency modulation issues, optimizing marine applications and enhancing operational reliability.

Roadmap for raising Technological Readiness Level of supercapacitors in marine

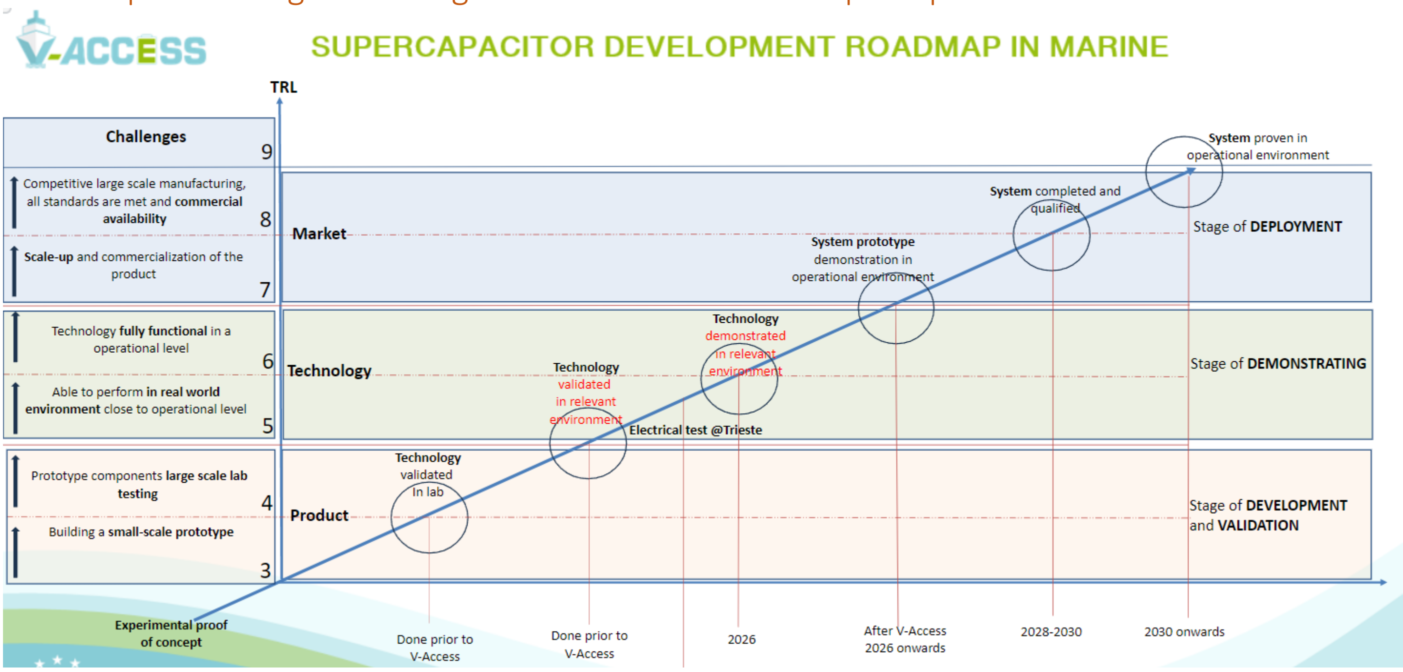


FIGURE 2 ROADMAP FOR RAISING TRL IN MARINE FOR SUPERCAPACITOR SYSTEMS

Although the supercapacitor system is already mature technology, its implementation in marine segment is still on low TRL. There are several regulatory and other constraints that need to be overcome to successfully

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use supercapacitor systems on vessels. In V-ACCESS context Skeleton Technologies supercapacitor system (Skelgrid 2.0 rack-based platform) is on TRL 5, which means that prototype components (sub-systems) have undergone large scale laboratory testing and whole system is ready for marine specific (real world environment close to operational level) tests. The first objective and challenge are to prove that the whole prototype is reliable in the relevant environment. This objective will be reached during testing according to V-ACCESS project WP3 T3.5 plan. To reach TRL 6 the main challenge is to find the place and resources to test full prototype close to operational level under controlled conditions and receive feedback to finetune first functional marine-specific version of the product.

Moving towards TRL 7 means that the stage of technology demonstration will be concluded, therefore the product needs to meet all operational and functional requirements to progress to the system demonstration stage. Main challenges between 6 to 7 is to test system successfully under real world conditions meaning whole system tests on actual vessels. Another time-consuming and costly process, which is a real challenge to new technologies, is product certification. For this strong market demand from potential customers and investors it is a necessity to progress there as quickly and market needs.

After TRL 7 and onwards a stage of deployment starts where the focus is on competitive manufacturing, which will be achieved through scale-up, commercialization and market strategy as well as emphasis on the readiness of the supply chain. More specifically the challenges between TRL 7 and 8 include acquiring system qualifications. This means all the technical documentation, compliance and certifications should be done so that focus can shift towards scale-up of production and product commercialization. A serious challenge to overcome is to find a qualified workforce who have experience in scaling up novel pilot productions. These skills are not so common in the EU market; therefore, it could be a significant obstacle to overcome. Another challenge is the lack of public funding that focuses on commercialization route for products that are novel and compete against conventional fossil-based solutions. In general technology development and even scale-up is being quite efficiently supported by the EU, however road-to-market and achieving compliance is clearly missing.

Reaching TRL9 and onwards it is all about competitive manufacturing and secure and efficient supply chains. This includes successful scale-up while maintaining supply chain security and access to a skilled workforce. Challenges are getting the costs down and having a clear market strategy. There are several areas where to implement supercapacitor systems in marine, each of the application areas having their own strengths and weaknesses against internal combustion engines or even electrical battery packs. It comes down to cost per kW and application time as was described in previous section about typical use cases in marine.

Roadmap for raising Technological Readiness Level of SMES in marine

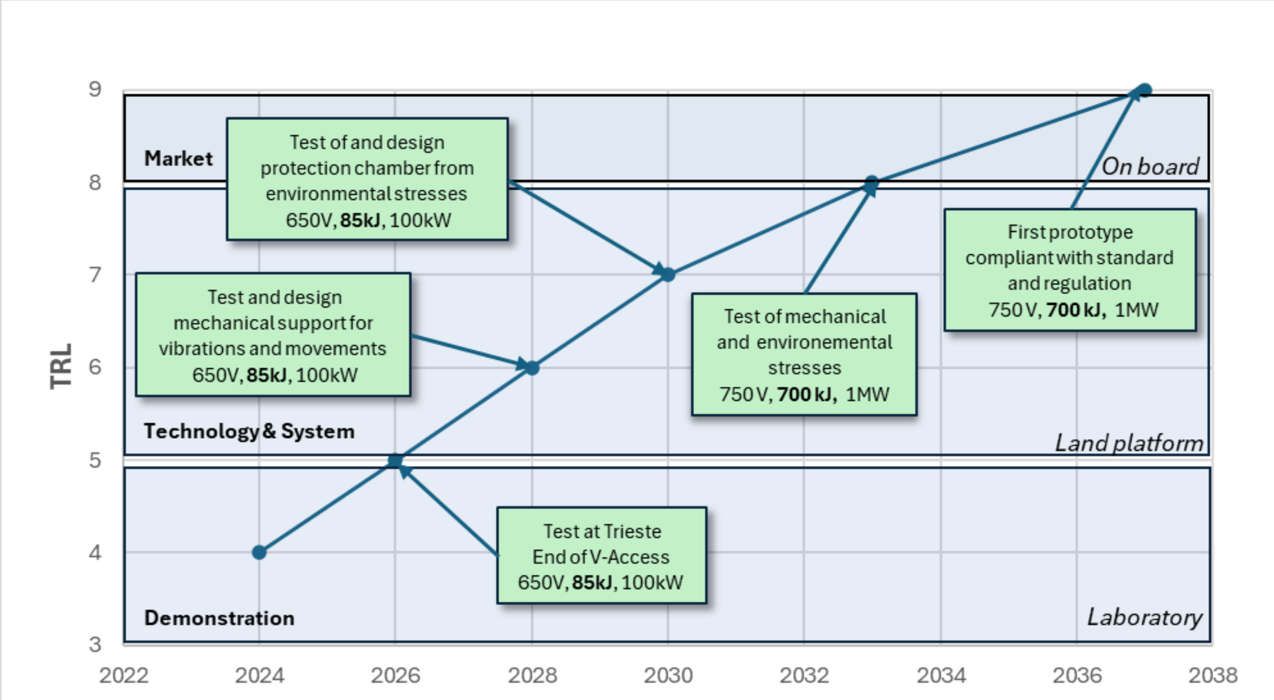


Figure 3 Roadmap for raising TRL in Marine for SMES systems

Although the SMES technology has been studied and demonstrated by the testing for more than 30 years, no large implementation has been yet realised. In any case the prototypes were designed and extensively tested with on-ground demonstrations in a similar or even higher power range. However, it has never been installed or implemented for the conditions of a ship. The timeline and required testing to achieve a TRL 9 envisioned is described into Figure 3.

As a starting point, ASG considers that the TRL 4 is reached as it is demonstrated already [6],[7],[8],[9]. It has been proven that different and repeated power profiles that include load and unload are manageable with SMES. The next level will be reached by testing the system that includes an adapted power converter in association with batteries. It will be done at the end of the V-ACCESS project on the Trieste test platform in collaboration with Trieste university during task 3.5. At the end of V-ACCESS project, an important step indicating that the SMES system can be proposed as an additional peak power source under low voltage of 650-750 V DC, the voltage on board of a ship. It will confirm the adequation of the SMES power source to the specific mission profiles on board a ship defined and tested. This work will be carried out on a smaller system up to 85 kJ that is in accordance with testing platform specification and budget of V-ACCESS project.

Hereafter a list of challenges reaching each technological readiness level is summarized:

TRL 3 to TRL 4 – Experimental proof of concept to technology validated in the laboratory

- Already demonstrated on a 20 kJ SMES system
- Lab tests & Computer simulations done

TRL 4 to 5 – Technology validated in lab to technology validated in relevant environment

- Validated after the completion by March 2026 (end of the V-ACCESS) of electrical power testing at Trieste on an 85 kJ 650 V SMES system, including:
  - Definition of power profiles including ramp up, ramp down, multi levels.
  - Acceptance of the safety procedure for the testing
  - Validation of the magnetic field compatibility (EMC) on the site and on-board a ships
  - Check the auxiliary connections (chiller, cooling fluid, electrical power…)

TRL 5 to 6 – Technology validated in relevant environment to technology demonstrated in relevant environment

- Validated by 2028 after the completion mechanical test simulating the stresses on board on an 85 kJ 650 V SMES system mechanically upgraded, including:
  - Definition of relevant mechanical profiles including oscillation, shock, vibration (amplitude, frequency, number of cycles)
  - Design and manufacture upgraded SMES system
  - Identify the possible land testing platforms
  - Design and manufacture the tooling for the testing
  - Acceptance of the safety procedure for the testing
  - Check the auxiliary connections (chiller, cooling fluid, electrical power…)

TRL 6 to 7 System prototype demonstration in an operational “environment “

- Validated by 2030 on land after the completion environment simulating the atmosphere (moisture, salt) on board on an 85 kJ 650 V SMES system mechanically upgraded, including:
  - Definition of environment profiles including duration and atmosphere (composition, temperature)
  - Design and prepare an environment protective enclosure that includes the SMES and its auxiliaries
  - Identify the possible land testing platforms
  - Design and manufacture the tooling for the testing
  - Acceptance of the safety procedure for the testing
  - Check the auxiliary connections (chiller, cooling fluid, electrical power)

TRL 7 to 8 - System completed and qualified

- Validated by 2033 after the completion of testing on land on an upgrade 700 kJ 750 V class SMES system mechanically compliant, including:
  - Design and manufacture a mechanically compliant 700 kJ class SMES system in its protective enclosure

  - Definition of testing profiles
  - Identify the possible land testing platforms
  - Design and manufacture the tooling for the testing
  - Acceptance of the safety procedure for the testing
  - Standard and regulation rules to be proposed

TRL 8 to 9 system proven in operational conditions

- Validated by 2036 after the completion of testing on board on a 700 kJ 750 V class SMES device
- Standard and regulation rules defined and accepted
- Identification of a test ships (Fery, Trawler, OSV) and an end user/customer contractually committed
- Test according to missions predefined.

Cost Targets and Economic Benefits of Integrating Energy Storage Systems (ESS) into Combined Solutions

The integration of Energy Storage Systems (ESS), particularly batteries and supercapacitors, into maritime applications is becoming increasingly viable due to technological advancements and decreasing costs. The maritime industry, traditionally dominated by diesel and other fossil fuel-based propulsion systems, is exploring battery and hybrid solutions to reduce fuel consumption, emissions, and operational costs. However, the economic feasibility of these solutions varies significantly across different vessel types, operational profiles, and market segments. This chapter aims to provide an overview of cost targets, payback periods, and the economic benefits associated with the integration of ESS in various maritime applications.

The cost of system integration for an electrical storage system can be significant and should be considered early in the adoption process. Total system costs include:

- Purchase Price: Includes power electronics, installation (including electrical work), Failure Modes and Effects Analysis (FMEA), modifications to the switchboard, commissioning, and testing.

- Lifetime Considerations: The lifetime of electrical storage depends on the duty cycle relative to the size. A smaller battery may have lower capital expenditure (CAPEX) but may not last as long as a larger battery for a given application. That is where a short-term high-power energy storage unit could be a feasible option to reduce the battery size.

Competitors in Marine Applications for high-power energy storage system

Supercapacitors

Eaton is a notable competitor in the marine energy storage market, particularly with its focus on supercapacitors. As the maritime industry increasingly seeks to reduce emissions and improve energy efficiency, Eaton's supercapacitors have emerged as an alternative to traditional battery systems, addressing specific power needs within marine environments.

Eaton's supercapacitors are designed to meet the challenging demands of marine environments. Marine vessels, ranging from sailboats to larger offshore ships, require reliable power solutions due to their size and operational needs. Traditional batteries, although widely used, face challenges such as limited lifespans, thermal management issues, and inefficiencies at extreme temperatures. In response, Eaton's supercapacitors offer an alternative that emphasizes longevity and operational stability, with lifespans extending up to 20 years in certain conditions.

A significant aspect of Eaton's supercapacitors is their ability to provide high power density, which is particularly useful in operations that demand short, intense bursts of power. These scenarios include engine starting and dynamic positioning, where performance reliability is critical.

Eaton's approach to supercapacitors in marine applications positions them as a competitor in the move towards more electrified maritime operations. While their solutions offer some advantages over traditional batteries, particularly in terms of power density and lifespan, the practical benefits depend on the specific application and operational environment.

As the maritime industry continues to explore electrification options, Eaton's supercapacitors represent one of several possible approaches to addressing the power and efficiency challenges faced by marine vessels. Their focus on integrating supercapacitors into hybrid power systems reflects a broader industry trend, although the ultimate effectiveness of these solutions will vary based on the specific requirements of the vessel and its operating conditions.

In conclusion, while Eaton's supercapacitors offer an alternative to conventional battery systems in certain marine applications, they represent just one of many strategies being explored within the industry to meet the evolving demands for sustainable and efficient energy storage solutions.

Superconducting magnetic energy storage

There is no real competition for SMES providing as the market is not yet established and its need is still emerging. As such SMES are still prototypes or proofs of concept in R&D projects. These systems are generally designed and managed by research institutes or universities. However, these institutes get the support by an ecosystem of industrial companies involved in superconducting magnets manufacturing to provide some elements of the systems. These companies are, however, very limited in numbers. In Europe compagnies like GE (France), Sigmaphi (France), Babcock Noell (Germany), Theva (Germany), Suprasys (Spain), Antec (Spain), ASG (Italy) can provided at least the superconducting coils in their cryostat. Out of Europe, some companies in Asia (Japan, Korea, or China) or USA and historically in Russia are also able to design and manufactured such system on the same bases. To our knowledge none of these companies has the complete skills alone. The full integration of the systems on board requires generally to being contacted by *Ad hoc* consortiums that include suppliers the cooling systems, power electronics, monitoring systems and on-board installation. However, indirectly all other high-power energy storage systems are competitive, especially the ones that have high TRL.

Cost of goods sold (COGS)

For accurate cost projection analysis, the Cost of Goods Sold (COGS) framework can be used structured around both component and system levels. This will enable us to understand cost dynamics as production scales up, ultimately leading to significant reduction in COGS. Analyzing COGS at both component and system levels provides insights into which areas have the most significant impact on overall costs at which scale. Understanding cost drivers is crucial, because it helps to identify opportunities for cost reduction, whether it is material sourcing or manufacturing optimization (usually both).

Another important aspect of COGS framework is that it helps to evaluate economic viability by projecting future costs based on current data before committing significant resources at mass scale. Therefore pilot-production is crucial step when moving up in TRL of new technology such as supercapacitors or SMES. It is clear from the framework that scale is important, and mass production can lead to significant reductions in COGS. Without this, it would be difficult to reinforce the need for investments, so that emerging technologies could launch onto the market.

The initial prototyping phase is the first stage, where there are lot of uncertainties and cost projection is based on several assumptions and does not show good accuracy. If the development progresses into further TRL stages, then the first real understanding of economic viability occurs. Subsequently, the pilot production phase starts. Then excessive costs incur primarily due to lower efficiencies, higher labor costs, and less optimized logistics compared to mass production.

As production scales up to mass production levels, the COGS decreases significantly due to:

- Economies of Scale: Bulk purchasing materials leads to lower material costs.
- Process Optimization: Enhanced manufacturing processes reduce labor and energy costs.
- Learning Curve Effects: Increased experience in production leads to improved efficiency.

Cost-of-Goods-Sold is the sum of all direct (and indirect) costs associated with making a product and can be summarized as the sum of “Operational Cost” and “Production Cost” divided by variable “Number of Production”.

The value of variable “Production Cost” is obtained from the sum variable “Total Raw Material Cost”, “Total Labor Cost”, and “Total Overhead Expenses” COGS (per kWh), which consists of “Overhead cost per kWh + Bill of Materials cost per kWh. Therefore, it can be summarized that COGS is the **absolute lowest price** to sell a product to break-even and does not include selling, administrative or other expenses associated with making a product.

Hereby an example for supercapacitor system list of COGS components is seen:

Production cost and overhead:

- Labor
- Cell assembly
- Module assembly

- Cabinet assembly
  - System assembly modules into cabinet
- Overheads
  - Cell overhead
  - Module assembly overhead

BOM (bill of materials) cost:

- Cell materials
  - electrodes, electrolytes, separators, containers
- Module BOM
- Master controller
- Cabinet
- Switchgear
- Packaging

Other costs

- Warranty
- Rework/scrap
- Risk
- Travel, certification etc.
- Transportation
- Warehousing

Based on quality data that make up complete COGS of the product, several analyses could be carried out. For example, to use extrapolation techniques to utilize historical data to project future costs using methods such as time series analysis and regression models. Also, conducting sensitivity analysis to assess how changes in key variables (e.g., raw material prices, production volume) impact overall costs.

The COGS framework in general should give a comprehensive understanding of where costs are incurred within the production process, enabling targeted interventions for cost reduction. Also, an adaptability to changing market conditions and technological advancements, making it robust against uncertainties.

To add an example here, Skeleton Technologies has witnessed the learning curve effect how COGS can significantly decline with increased production volumes. From the first prototyping stage to the pilot production the difference could already be 5-fold cost reduction. Depending on the scale of the first pilot the additional reduction from mass production is projected significant 40-50%. To understand whether the decrease in COGS through mass production outweighs the risks associated with scaling up production such as supercapacitor manufacturing, it is essential to conduct a comprehensive risk-benefit analysis. This would include:

1. Cost Analysis and current COGS comparison:

  - Pilot vs Mass-cale production projected savings: 40% reduction per unit when scaling up.

2. Identifying Risks of Scale-Up:

- Supply Chain Challenges:
  - Potential disruptions in the supply of raw materials (e.g., electrodes, electrolytes).
  - Increased demand may strain existing suppliers or require new partnerships, leading to potential delays and cost increases.
- Qualified Workforce:
  - The need for skilled labor increases with scale; training and recruitment can be time-consuming and costly.
  - Retaining qualified personnel becomes crucial as competition for talent intensifies.
- Energy Demand:
  - Higher production volumes lead to increased energy consumption, which could raise operational costs.
  - Fluctuating energy prices can impact overall profitability.

3. Risk Mitigation Strategies

- Supply Chain Management:
  - Establish multiple suppliers for critical components to reduce dependency on single sources.
  - Implement just-in-time inventory practices to minimize excess costs while ensuring availability.
- Workforce Development:
  - Invest in training programs to upskill existing employees and attract new talent.
  - Foster a positive workplace culture to enhance employee retention.
- Energy Efficiency Initiatives:
  - Explore renewable energy options or energy-efficient technologies to mitigate rising energy costs.
  - Conduct energy audits to identify areas for improvement in production processes.

4. Quantitative Risk Assessment

- Scenario Analysis:
  - Develop best-case, worst-case, and most-likely scenarios for each risk factor.

- Estimate potential cost impacts of each risk on overall COGS and profitability.

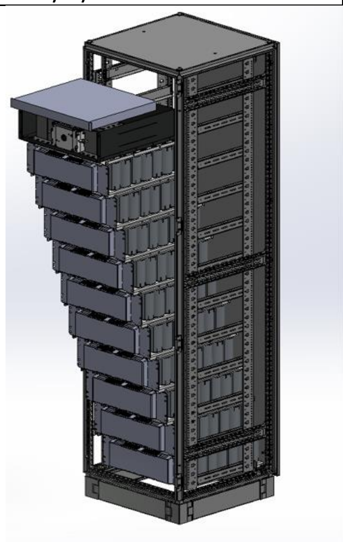
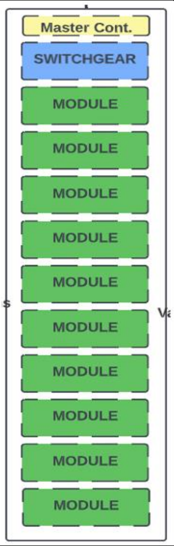
- Break-Even Analysis:
  - Calculate the volume of production needed at the lower mass production COGS to cover potential increased costs from identified risks.

By conducting a thorough analysis that includes both the projected decrease in COGS and the associated risks of scaling up production, stakeholders can make informed decisions. If the projected savings from mass production significantly outweigh the potential costs arising from supply chain issues, workforce challenges, and increased energy demands, then scaling up can be justified. This structured approach allows companies to balance the benefits of reduced COGS against the inherent risks of scaling, ultimately guiding strategic decisions in the development and commercialization of supercapacitors.

Supercapacitor cost analysis

As mentioned, supercapacitor COGS from prototyping stage to piloting to mass production is expected to come down 5-fold, but there are several uncertainties still. Most accurate cost projections can be made for subsystem components such as supercapacitor electrodes, electrolytes, current collector foil, and even for the whole cell. Module development, taking into consideration software and hardware engineering and testing, validation, are more and more difficult to factor in. From the modules also the systems are assembled, which also consist of units such as supercapacitor-management-system, switchgear units and even fan for cooling the modules. During V-ACCESS a whole system is analyzed, which makes the cost projection more challenging.

TABLE 3. SUPERCAPACITOR SYSTEM INDICATIVE COST PER SELECTED USE CASES

	Ferry system	OSV AHC system	Trawler
			 + Rated voltage 162 Vdc + Capacitance 62 F + Rated DC 1s ESR 13 mΩ + Energy (for: V_{rated} – ½ V_{rated})* 169 Wh + Mass 35 kg + Dimensions (WHL in mm) 483 x 178 x 540
Configuration	5s6p (five modules in series with six parallel strings fitting into three 19’’ cabinets)	5s2p (five modules in series with two parallel	1s1p (one module consisting of 54 supercapacitor cells in series)

		strings) fitting into one 19'' cabinet	
Energy	4.3-5.4 kWh	1.36-1.7 kWh	0.133-0.17 kWh
Power (1s)	+2 MW	+2 MW	+100 kW
Weight	1000kg	330 kg	33-35kg
Footprint area	One square meter plus operation/maintenance room	0.36 square meters	0.36 square meters
Prototype COGS	50k€/kWh and 150€/kW	50k€/kWh and 150€/kW	35k€/kWh and 60€/kW
Pilot-scale COGS	14k€/kWh and 40€/kW	15k€/kWh and 12€/kW	Below 10k€/kWh and 16€/kW
Scaled-up COGS	Below 10k€/kWh and 28€/kW	11k€/kWh and 9€/kW	8k€/kWh and 14€/kW

In Table 3 COGS projection is seen based on three customer use cases analyzed during V-ACCESS project. Costs are shown per kWh and per kW, as the short-term energy storage systems, such as supercapacitors and SMES, do not contain a lot of energy compared to energy dense battery systems. Therefore, price per kW could be a more suitable comparison depending on the application.

Hybrid system analysis

High-power short-term energy storage systems such as supercapacitors or SMES generally have high efficiency under high power loads; therefore, hybrid systems (together with batteries) generate less waste heat than an energy storage solution based solely on LIBs. As less heat needs to be transported away from the LiB pack, cooling systems can be downsized leading to the cost impact of hybrid technology compared to LiB modules. The cumulated effects of needing less cells for the same performance, reducing cooling efforts and decreasing overall system weight can result in an overall system cost reduction of up to 30% when compared with similarly performing LiB-packs.

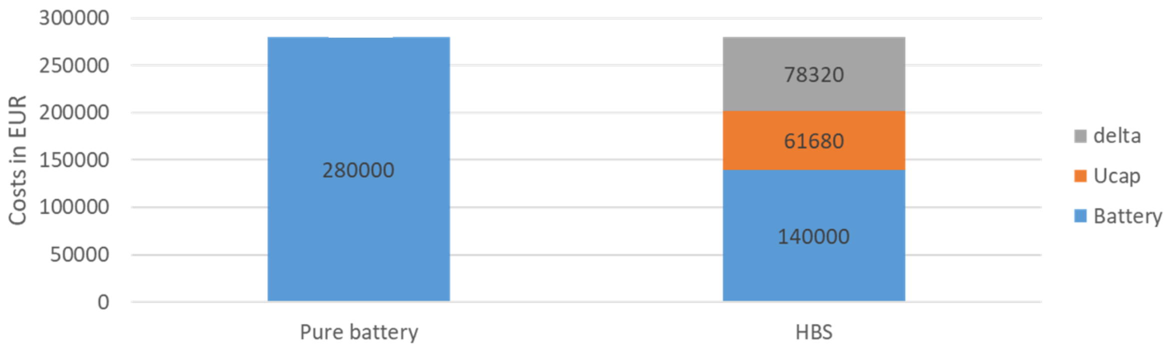


Figure 4 Cost comparison for a system capable of providing a 10 s 800 kW pulse. Assumptions for LIB are: 1 C max. discharge rate (for optimal lifetime and comparable cooling), 350 EUR/kWh[1], 800 kWh system. Assumptions for HBS are: 400 kWh battery system, 400 kW Supercapacitor system. Supercapacitor system is priced within today's price range.

The hybrid systems can be smaller and lighter, as batteries do not have to be scaled for power when combined with supercapacitors or similar technologies. As the lifetime of a battery improves greatly (50 – 100%) when applying hybrid logic, the respective systems can also be made smaller due to a larger retention of energy storage capability over lifetime.

TABLE 4 KPIS FOR A STATIONARY SYSTEM CAPABLE OF DELIVERING A 10 S, 800 KW PULSE AND A 400 KW BASE LOAD FOR 1 HOUR. IT CAN BE SEEN THAT THE HBS SYSTEM SUPPLIES THE CHEAPEST, LIGHTEST AND MOST LONG-LIVING SOLUTION FOR THE APPLICATION.

System	Cell cost in EUR	Maximum Power in kW (<5 s)	Energy in kWh	Cell Weight in kg	Lifetime in high power cycles
SC-based[2]	1,800,000	2,659,280	400	78,500	1,000,000
LIB, high energy[3]	280,000	800	800	3,200	1,500
LIB, high power[4]	320,000	4,000	400	3,300	10,000
HBS 2019	222,000	10,200	400	2,800	1,000,000
HBS 2023	152,000	4,100	400	2,100	1,000,000

Cost analysis of SMES

SMES is not yet a commercial product and today are only manufactured as prototypes. Until now there is no mass market of SMES system. Its production is not yet fully mature and still needs development, adjustment and testing that will impact its costs. It is difficult to estimate the business, but it is expected that cost reduction will happen according to the demand and production rate.

One option is to compare to the path followed by the market of superconducting MRI systems in the last 30 years where a rationalisation of manufacturing processes and of their components have been carried out. The cost of such system has come down at least by 2-fold since the first commercialisation of the product. Even if MRI systems are larger and more complex systems compared to the SMES systems envisioned in V-ACCESS, these are the closest commercial systems to study SMES. Today MRI magnets are produced in small series. The world production of MRI magnets is approximately 2500 systems per year with approximately 36000 already installed since the 1980. The yearly revenue generated by this market was about 6,7 billion $ in 2023 that gives an average price of 2,6 million $ per MRI systems. This price includes the imaging system that is not necessary for a SMES on board a ship.

Using an approach inspiring on the MRI magnet market, the investment price for the shipyard of a SMES systems in similar small series is foreseen is below 200 k€ per single system including the cooling system and auxiliaries for a market of about one hundred of systems per year. If necessary, several SMES systems can be for connected as independent bricks to raise its power like battery packs. As shown below, the main components are independent of the energy stored except the superconducting wires and DC-DC converter.

[2] Assumption: 4500 EUR/kWh, Power to energy ratio: 2720 W/Wh, 6.8 Wh/kg
[3] Assumption: 350 EUR/kWh, Power to energy ratio: 1 W/Wh, 250 Wh/kg
[4] Assumption: 700 EUR/kWh, Power to energy ratio: 10 W/Wh, 120 Wh/kg

Figure 6 shows the arrangement of the different components and Table 6 is giving an estimation of the main components costs according to the cases analysed in V-ACCESS.

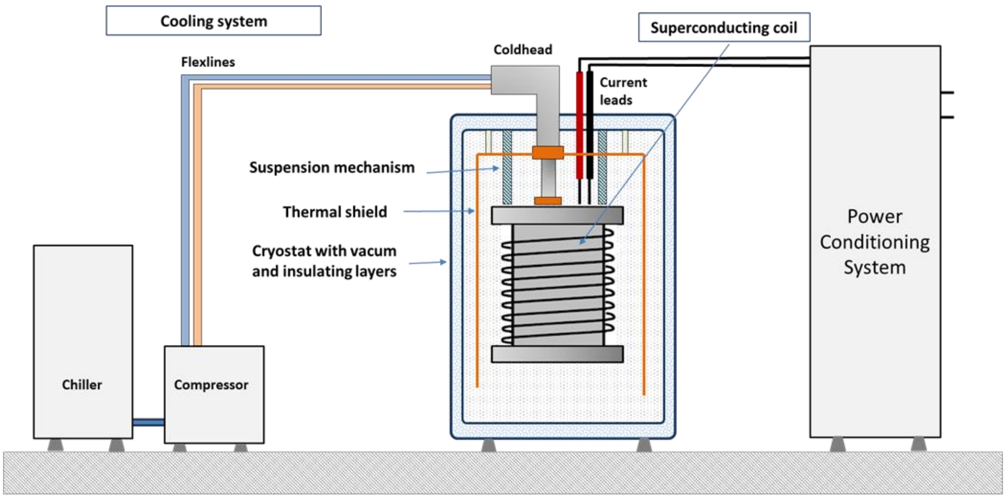


FIGURE 5 SMES CONCEPTUAL SCHEME

The systems discussed here includes the cryogenic cooler and its accessories. The cryogenic costs cost can be mutualized with other equipment on board or even reduced if cryogenic fuel is used on board the ship as liquid H_2 or even LNG. As the stray field generated by the SMES coil is considered acceptable on board for the three use cases, the systems investigated do not include any active magnetic shield. The marinization is not considered in this table, but we can imagine placing the overall system in a container where the atmosphere is controlled for a price approximately of 5000 €.

TABLE 5 COST IN € OF THE DIFFERENT ELEMENTS OF THE SMES SYSTEM

Business Cases		750 kJ Ferry	350 kJ OSV	85 kJ Trawler *V-ACCESS demo*
Operating current		Iop 470 A	Iop 400 A	Iop 250A
Superconducting coil	Superconducting wires cost and length	30000 (10 km)	18000 (6 km)	12000 (4 km)
	Winding coil element (Mandrel thermal link)	11000	11000	4500
	Cryostats and thermal shield	30000	25000	20000

	Current leads	3500	3500	2700
Cooling system	Cryocooler and compressor	50000	40000	40000
	Chiller	5000		
	Thermometers	3000		
	Vacuum Jauge (primary & secondary)	1000		
DC-DC Converter 650 to 750 V class with a dump resistance for fast discharge		30000 *(200 kW)*	30000 *(200 kW)*	25000 *(160 kW)*
Control system	Control unit computer	5000		
Manpower	Manpower for manufacturing, quality control and Installation	20000		
Total cost		188500	160500	137200

The cost of a SMES system is mostly given by the superconducting coils in its cryostat and the cooling system. These two elements take more than 60% of our estimation. If a cryogenic system or cryogenic fluid tank (LNG, liquid H^2 as fuel) exist on board for other needs, the use of a dedicated cooling system can be reduced to a circulating pump and a heat exchange. Consequently, the cost of the cooling system is expected to decrease by at least two-fold. In addition, in this case the dedicated chiller is dispensable.

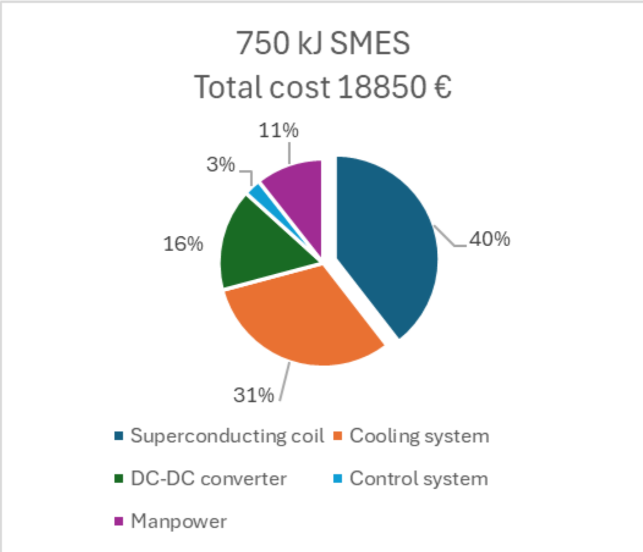


FIGURE 6 EXAMPLE OF THE DISTRIBUTION OF THE COST DISTRIBUTION FOR A 750 KJ SMES.

These costs are estimated for small series up for few of systems per year. In case of the manufacturing of hundreds of SMES system as for MRI magnets, significant cost reduction is expected that can goes rapidly at least up to 30% and probably to 50% when the production in series starts.

In this range of stored energy, the overall cost of a SMES system is only lightly dependant on the stored energy. In any cases, it requires a cryostat a cooling system with a small dependence from the stored energy. At the contrary, the cost of the coil is fully dependent on the SMES storage capacity due to the quantity of MgB_2 wires winded. The larger the stored energy the more cost efficient a SMES system.

The DC-DC converters are based on existing and commercial power blocks that can deliver a voltage up to 500A under 750 V. No development of the software for the controller of DC-DC controller is envisioned after V-ACCESS project.

Conclusions

An in-depth analysis of the readiness level of the supply chains, production processes and product specifications of SMES and supercapacitors was carried out. High-power short term energy storage systems were also compared to more conventional battery systems. Based on this analysis a roadmap for increasing the TRL and for a Go-to-Market-Strategy in marine of the supercapacitors and SMES can be derived. However, supercapacitors are mature technology their applications in marine are still in low TRL, therefore this analysis is important and even for SMES, although this technology has been studied for many years, the product is still not yet commercialized. Many SMES prototypes have been successfully tested based on different superconducting technologies since 1980 but due to its size and cost it has stayed in low TRL. Nowadays, thanks to the high temperature superconductors, SMES can be reconsidered as an electrical power source in marine applications. A testing and validation program for SMES is proposed in this report. When it will be carried out in full qualification for power supply onboard a ship is foreseen to be achieved in 2035. As a first step the testing in V-ACCESS project on Trieste test platform is an important milestone in 2025.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Sources

- Arellano, H. et al. (2022). "Energy Storage Systems: An Overview of the State-of-the-Art." SINTEF. Link
- Barros, A. (2020). "Technical Paper on Supercapacitors for Marine Applications." INEC 2020. Link
- Battery Industry Tech. "New Energy Storage Technology EU Project V-Access." Link
- Danube Commission. "Zero Emission Strategy: SRIA ZEWT IWT." Link
- Eagle.org. "Supercapacitors Requirements." Link
- EMSA. (2020). "Study on Electrical Energy Storage for Ships." Link
- EIT. "White Paper on Supercapacitor Technology." Link
- EU Project V-Access. "Press Release." Link
- Horizon Europe NCP Portal. "EMSA Study on Electrical Energy Storage for Ships." Link
- RINA.org. "V-Access Project Case Study." Link
- Southampton University. "The Future of Batteries in the Marine Sector." Link
- STEPS Report. "State of the Art in Marine Energy Storage." Link
- Supercapacitors Technical Note. "Supercapacitors for Marine Applications." Link
- 63rd Naval Engineering Congress. "Fast Response Energy Storage Systems for Marine Applications." Link
- Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany, S. Árpád Funke, P. Plötz, M. Wietschel, *Applied Energy*, **2019**, *235*,888-899.; EASE/EERA European Energy Storage Technology Development Roadmap.
- Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany, S. Árpád Funke, P. Plötz, M. Wietschel, *Applied Energy*, **2019**, *235*,888-899.; EASE/EERA European Energy Storage Technology Development Roadmap.
- [1] C. A. Luongo, "Superconducting Storage Systems: an overview", *IEEE Transactions on Magnetics*, vol. 32, 1996, pp. 2214-2223.
- [2] Ciceron J, Badel A, Pascal Tixador P, Forest F 2017 Design Considerations for High-Energy Density SMES *IEEE Trans. Appl. Supercond.* **27** 5700705

- [3] Charles C. “Developmental Challenges of SMES Technology for Applications” 2017 IOP Conf. Ser.: Mater. Sci. Eng. 279 012013
- [4] C.Gandolfi, Chiumeo R, Raggini D, Faranda R, Morandi A, Ferdeghini C, Tropeaono M Turtu s, “study of universal power SMES compensator for LV distibution grid “ AEIT 2018 DOI: 10.23919/AEIT 20218 8577335
- [5] Online https//op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1 (2023)
- [6] Morandi A, Fabbri M, & al “Calculation of AC losses in a- 500 kJ /200 kW multifilamentary MgB2 SMES coil” Energies 2023 journal article DOI: 10.3390/en16041596
- [7] J. Vialle, A. Badel, K. Takahashi, S. Awaji, P. Tixador *“A High Performance Insulated REBCO Pancake With Conductive Cooling Capability »* IEEE Transactions on Applied Superconductivity, vol. 33, 4600405, 2023.
- [8]J. Vialle, A. Badel, P. Tixador*“12 T insulated REBCO magnet used as 1MJ SMES protection strategies and preliminary assembly test »* IEEE Transactions on Applied Superconductivity, vol. 32, 4702307, 2022.
- [9] J. Vialle, A. Badel, P. Tixador, J. Cicéron, F. Forest, R. Pasquet *“Preliminary Tests of Pancakes From a 12 T REBCO Insulated Solenoid Magnet”* IEEE Transactions on Applied Superconductivity, vol. 31, 4600805, 2021.