

Enhancing offshore hybridization via storage: Technical and safety consideration in Blue Economy projects

E. Nanini-Maury, A. Castets, L. Nadau, and D. Corbisier

Abstract—Energy storage systems (ESS) are crucial for integrating renewable energy sources, enhancing system flexibility, and meeting grid restrictions. The selection of an energy storage system technology depends on factors such as availability, maturity, geographical conditions, local regulations, space constraints, safety, raw material availability, deployment time, and CAPEX. Key evaluation parameters include energy density, energy/power ratio, expected lifetime, safety risks, and mitigation strategies. In Blue Economy projects (i.e. Offshore Renewable Projects), site conditions significantly influence the energy storage system's choice. The FORWARD2030 EU project, in which ENGIE LABORELEC is a project partner, aims to demonstrate a zero-carbon energy system combining wind and tidal energy with several ESS. Simulations showed that coupling tidal production with a 1MW/1MWh storage solution, requiring 236 cycles per year, optimizes performance. For this project, ESS technology selection considered market availability, safety, and Technology Readiness Level. Special attention was given to safety, particularly for lithium-ion batteries, which pose thermal runaway risks. Mitigation strategies include material selection, integration, and installation, ensuring compliance with international safety standards. By addressing these considerations, the project aims to integrate lithium-ion batteries effectively and securely, supporting a viable zero-carbon energy system.

Keywords—Battery, Energy Storage System, Offshore energy, Return on Experience on projects, Safety.

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I. INTRODUCTION

Storage solutions can be coupled with offshore Renewable Energy Sources (RES) such as tidal and wind generators among many others to bring extra flexibility to the system. A wide array of energy storage technologies exists, encompassing mechanical, thermal, electrostatic, chemical, and electrochemical processes. Energy storage systems (ESS) can be integrated with RES to enhance system flexibility as well as comply to grid restrictions. The selection of an appropriate technology depends on various project-specific factors, including availability, maturity, geographical conditions, space constraints, safety constraints and attentions, raw material availability, deployment time, and CAPEX that aligns with the project's budget.

Key parameters to select the correct solution include energy density, energy/power ratio, expected lifetime, safety risks, and mitigation strategies. In Blue Economy projects, the location and site conditions also significantly influence the ESS choice. To illustrate it, a return on experience based on the FORWARD2030 EU project will be used, in which ENGIE Laborelec is a partner.

One of the Project's goals is to demonstrate the feasibility of a zero-carbon energy system that combines wind and tidal energy with energy storage solutions. To minimize energy curtailment through dynamic limitation, simulations were conducted to assess the impact of integrating an ESS to enhance tidal energy grid injection potential. The results indicated that optimal performance for the given site and project specificities would be achieved by coupling tidal energy production with a 1MW/1MWh storage solution, requiring a minimum of 236 charge/discharge cycles per year.

To select the right project specific technology, different aspects must be considered: market availability, safety aspects, and Technology Readiness Level (TRL) to ensure feasible installation and operation within the project's timeframe. Special attention has to be given to the safety aspects including an overview of the main hazards associated with offshore energy projects, as well as a review of relevant safety standards and best practices.

II. TECHNOLOGY SELECTION FOR BLUE ECONOMY PROJECTS. CASE STUDY: FORWARD2030 EU PROJECT

A. Simulation results and performance optimization for coupling tidal energy with ESS

Different scenarios were evaluated to enhance tidal flexibility, considering the current layout of the targeted site and the future layout anticipated under the FORWARD2030 project (Fig. 1. Site overview. Fig. 1). The scenarios aimed to:

- Shave high power variation of tidal turbines and reduce grid capacity requirements.
- Minimize high-frequency active power variations.
- Provide balancing services to the grid operator.
- Improve green hydrogen production.

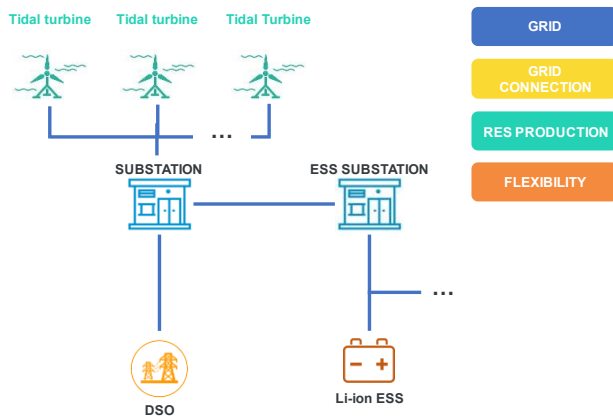


Fig. 1. Site overview.

One specific scenario focused on minimizing energy curtailment through dynamic limitation (including grid restrictions). Simulations were conducted to assess the impact of integrating an ESS into the system to enhance tidal energy grid injection potential. The hypothesis assumed a total energy production 25GWh per year. Then, a mapping of ESS power and energy suitability was performed to determine the optimal balance between the number of cycles per year and the amount of yearly curtailed energy.

The main result indicated that the optimal solution involves coupling tidal energy with a storage system from 1MW/1MWh, with a minimum of 236 cycles per year. This configuration results in an annual curtailment of up to 3.0%, preventing the loss of 250 MWh each year. To implement this solution effectively, the ESS technology must be selected based on additional criteria such as market availability and TRL. This ensures that installation, operation, and data analysis can be effectively carried out within the timeframe of the FORWARD2030 project.

B. Technology selection criteria

Depending on the project's constraints (e.g. geographical conditions, available place, raw materials

availability, deployment time, maximal acceptable CAPEX), different technologies may be suitable. The scope is restricted to electrical energy as input and output and considers both non-electrochemical and electrochemical technologies.

Table I thereafter shows the suitability of various technologies for the current project. Based on this evaluation, three electrochemical technologies have been considered: Li-ion, redox flow and lead-acid batteries. For lithium-ion technologies, different configurations are evaluated, including containerized racks with integrated modules suited for stationary applications and packs designed for electric vehicles, which can be proposed by integrators as an alternative to stationary modules.

TABLE I
SUITABILITY OF THE STORAGE TECHNOLOGY WITH FORWARD2030
PROJECT'S REQUIREMENTS AND MAIN REASON WHEN NON-SUITABLE

Category	Technology	Suitable? (Y/N)	Comments
Non-electrochemical	CAES	N	Too large footprint
	PHCA	N	Need for 2 basins at 2 different altitudes
	LAES	N	Could be envisaged onshore, but too low maturity
	Gravity Energy Storage	N	Too low maturity
	Flywheel	N	Low REX (not enough competition)
	Carnot battery	N	Large footprint and long deployment time
	Supercapacitors	N	Too fast discharge time
	SMES	N	Too expensive or too low maturity
	Li-ion	Y	
	RFB	Y	
Electrochemical	Lead Acid	Y	
	NaS	N	Not suitable for safety aspects
	Other technologies	N	Too low maturity

C. Electrochemical storage solutions

This section focuses on electrical energy as both the input and output. The following parts will provide a description of each energy storage technology considered, including a description of its working principle, design and characteristics, as well as its advantages and drawbacks.

An electrochemical storage solution is based on oxidation-reduction reactions (RedOx reactions). A rechargeable solution can be recharged after a discharge (secondary systems). During the charge process, electrical

energy is converted into chemical energy and stored, while during discharge, the stored chemical energy is converted back into electrical energy for use.

Batteries are a type of electrochemical storage solutions. They vary based on the type of electrolyte, the nature of the electrodes, and the membrane types used. Different combinations of these major components can significantly affect overall performance, including energy and power densities, and lifespan. Operating conditions also vary depending on the specific battery technology and sub-technology. Not all battery technologies are equally mature. While some, like metal-air, sodium-ion, and solid-state batteries, are still under extensive research, others, such as lead-acid batteries, have reached their final stage with little potential for further technical improvements in terms of technology, manufacturing, or design.

1) Lead acid batteries

Lead acid is one of the oldest rechargeable battery technologies. Its maturity is high and the working principle is well known. Electrodes are made of lead (Pb) and lead dioxide (PbO₂) that are immersed in acid electrolyte (aqueous). During discharge, each electrode is converted to lead sulfate (PbSO₄). When recharging (during charge), the PbSO₄ is converted back to H₂SO₄, leaving a layer of lead dioxide on the cathode and pure lead on the anode. Several geometries and configurations are possible for this technology. Batteries are either valve regulated lead acid (or VRLA) or vented (also called flooded).

Compared to other battery technologies, interest for lead acid technology is risen by the following advantages: Low cost, relatively low initial investment; well established recycling; mature and reliable; robust, no complex cell management needed; tolerant to overcharging; low self-discharge.

However, some issues remain: danger of overheating, sensitivity to temperature; limited time without recharging between manufacturing & installation, low energy density compared to Li-ion (below 60Wh/kg vs. up to 260Wh/kg for Li-ion); low cycle life (500-1 000 cycles vs. 500-10 000 cycles for Li-ion); high maintenance required, especially for open versions where water has to be added; not environmentally friendly (acid and lead are toxic); ventilation requirement (H₂ gassing); technology seems to have reached its maximum in term of performance.

2) Lithium-ion batteries

Lithium-ion (Li-ion) battery technology belongs to the metal-ion chemistry family. During discharge, Li⁺ ions migrate from the negative electrode (anode) to the positive electrode (cathode) through the electrolyte. Conversely, during charging, Li⁺ ions return to the negative electrode, intercalating into the graphite layer. The cycling performance of Li-ion batteries can be

significantly influenced by the choice of materials for the electrodes and electrolyte. Currently, a limited range of components is utilized for the electrodes, with all products employing liquid electrolytes.

The most important advantages of Li-ion batteries are their global high energy density, limiting the footprint, and their versatility, allowing for their use in a lot of different applications, from mobility to stationary. On the other hand, Li-ion safety has to be controlled, through a sophisticated Battery Management System (BMS) and multiple safety measures to be taken into account from the cell design to the battery design. Those drawbacks contribute to a CAPEX that is still high today.

3) Redox Flow Batteries

The redox flow battery (RFB) technology is different from traditional battery technologies in its design. the RFB is made of pumps, stack and tanks. Generally, one stack is linked to only two tanks. The stack is composed of multiple cells where the electrodes are based on a porous carbon structure separated by an ion exchange membrane. The stack is where the electrochemical reaction takes place. The electrolyte is stored in two external tanks, linked to the two half-cells of the reaction. The electrolyte is called anolyte on the negative electrode side, and catholyte on the positive electrode side. Electrolytes act as liquid energy carriers, and the two parts are pumped simultaneously through a membrane separating the two half-cells of the reaction. Depending on the chosen technology, different metal ion valence can co-exist during cycling. With this type of design, power and energy are scalable independently. To add power, the reactive surfaces of the electrodes have to be enlarged while to add energy, there is the volume of electrolytes contained in tanks that has to be increased.

Compared to Li-ion batteries, RFB technology present the following advantages: active materials used for RFB are simpler to produce, which could have an impact on the CAPEX; cycle and calendar life of RFB are also a lot larger than Li-ion batteries (3 000-20 000 cycles and up to 20 years for RFB vs. 500-10 000 cycles and up to 10 years for Li-ion batteries); the safety inherent to the RFB chemistry is higher than for Li-ion batteries, where no thermal runaway is reported. However, a proper management of H₂ produced as side reaction during operation and electrolyte spill during maintenance is comparable to the standards already applied and followed for lead acid technology. RFB batteries are less sensitive to temperature increase compared to other technologies, thus, the cooling device for RFB is much simpler than for Li-ion.

On the other hand, this type of battery is less deployed than lead acid or Li-ion batteries, and the maturity and return of experience is consequently lower. RFB technology is also globally less performing than Li-ion batteries, particularly because of low energy and power densities (10-75Wh/kg for RFB vs. 80-260Wh/kg for Li-ion

batteries, depending on subchemistry for both technologies). The maintenance needed for RFB is mainly caused by corrosion of some specific parts due to the corrosive nature of the electrolyte. As such, the electrolyte lasts longer than other known technologies, leading to a better capacity retention and having maintenance mainly for mechanical parts.

III. IMPACT OF SPECIFIC LOCATION ON ESS CHOICE IN BLUE ECONOMY PROJECTS. CASE STUDY: FORWARD2030 EU PROJECT

There are examples of batteries already used in marine environments. The technologies already on the market are Li-ion and lead acid batteries. They are used on fixed offshore platforms (Li-ion containers), in boats (as fuel replacement or else) and in submarines (as fuel replacement). Depending on the external conditions, some storage technologies could be used, and others should be excluded.

D. BESS in tidal turbine

Before installing the BESS inside a tidal turbine, several requirements must be considered to ensure compatibility. The turbine of the FORWARD2030 project features a sealed compartment for the battery, with a risk of submersion. A 20ft container can fit inside the turbine and be installed through the front opening onshore, passing through the doors. The floor inside the turbine is flat but may tilt 15-20° due to sea movements, and the battery system would be bolted to the structure. Various sources of vibration, such as waves, rotating machinery, and vortex-induced vibrations (VIV), necessitate physically attaching the battery to fixed parts of the turbine to minimize vibration impact.

Additional constraints to consider for a BESS installation in a tidal turbine are the following

- **Accessibility:** The installation of a BESS in the dedicated compartment is accessible onshore. Minor maintenance will be performed offshore, and the turbine will not be brought onshore during its lifetime. The maintenance of specific elements will depend on the size and the conditions to replace it.
- **Weight:** The battery system will be mounted on a skid, which should not exceed 5 tons. The skid must be designed to handle point loading and operational loads.
- **Environmental Impact:** The temperature inside the turbine is maintained between 18-22°C. The compartment is sealed to prevent salt ingress, and relative humidity is around 60-65%. Salty and humid air can enter when the compartment is opened.
- **Safety Measures:** Fire detection and alarms are present. There is no forced ventilation inside the battery compartment, but it can be added if necessary. The compartment is not

explosion-resistant and is rated for an internal pressure of 2.5bar. Additional safety measures may be required depending on the selected technology.

E. BESS on offshore connection hub

When installing a BESS on an offshore fixed or floating platform, the following conditions must be considered. The battery can be installed either outside or inside in a dedicated battery room. An external placement exposes the battery to further temperature fluctuations, salt, and humidity as well as to submersion risk. Space availability depends on the platform configuration and must be assessed on a case-by-case basis. Accessibility to the platform is influenced by the meteorological conditions. In case of an incident, reaching the platform may take time due to its distance from shore.

Additional constraints include the need to securely anchor the battery system to the platform to prevent slipping and limit movement, whether inside or outside. Lightning protection must be considered for the battery system to avoid temperature-related damage. Additional measures depend on the platform configuration, such as maximum weight capacity and planarity. Existing alarms and safety measures must be evaluated to determine if additional ones are needed, and procedures for gas evacuation and fire incidents must be addressed.

F. BESS onshore

As with installations inside a tidal turbine or on an offshore platform, several constraints must be considered for a battery system installed onshore. In the FORWARD2030 project, the main difference from a standard battery installation is the remote location in a marine environment of the project site. The storage system can be installed outside, in direct contact with the elements, or inside a closed or partially closed building, protected from direct exposure to the marine environment. Coastal air is filled with humidity and salt, leading to accelerated corrosion (rust) if the system is installed outside. This drawback could be mitigated if the system is installed in a building, even if partially open. The impact of humidity and salt is more significant on electrical equipment and on the protective paint than on the electrochemical part itself. The external temperature seen by the BESS depends on the location. Coastal areas often face flooding risks, especially if the battery is located at sea level. This risk is mitigated if the battery is installed at a higher elevation. The road to the battery system must be passable to allow for maintenance without access difficulties. In case of an incident, the system should also be accessible to firefighters.

TABLE II
SUMMARY OF TECHNOLOGY SUITABILITY FOR POTENTIAL LOCATIONS

Possible BESS location	Technology	Suitability	Comments
BESS in tidal turbine	Li-ion (rack)	Yes if	Enclosure and additional safety measures needed
	Li-ion (pack)	No	Logistics associated to a pack replacement is identified as an issue in this configuration
	V-RFB	No	Floor tilt and vibrations are identified as an issue in this configuration
	Lead-acid	Yes if	Additional safety measures needed
BESS on offshore connection hub (inside)	Li-ion (rack)	Yes if	BESS must be compliant with an indoor installation Indoor must be compliant with the last available safety standards
	Li-ion (pack)		
	V-RFB		
	Lead-acid		
BESS on offshore connection hub (outside)	Li-ion (rack)	Yes if	Enclosure must be compliant with external conditions
	Li-ion (pack)		
	V-RFB		
	Lead-acid		
BESS onshore (inside a building)	Li-ion (rack)	Yes if	At higher level than flooding risk BESS must be compliant with an installation in a building Installation in a building must be compliant with the last available safety standards
	Li-ion (pack)		
	V-RFB		
	Lead-acid		
BESS onshore (outside)	Li-ion (rack)	Yes if	At higher level than flooding risk Enclosure must be compliant with external conditions
	Li-ion (pack)		
	V-RFB		
	Lead-acid		

A summary of the suitable technologies considering the potential locations is provided in Table II. Taking the project's constraints (technical & non-technical e.g. regulation, costs) into account, a final decision was made to install a lithium-ion BESS onshore, placed outside in a

container. The specific implementation and best practices for this configuration is described in the next part, covering elements such as safety, electrical integration, and control.

IV. IMPLEMENTATION AND BEST PRACTICES

G. Main hazard of lithium-ion technology

Three main criteria are often considered by industrials: safety, performance, and cost. In practice, safety must be prioritized to ensure the highest standards are met. Achieving the highest level of safety for a project requires a thorough understanding of the primary hazards and their consequences, as well as the current standards and good practices. This will allow to develop effective mitigation strategies.

Lithium-ion batteries, while highly efficient and widely used, present specific hazards that must be carefully managed. One of the critical safety concerns of this technology is thermal runaway, a self-sustaining reaction where the battery overheats and potentially catches fire or explodes. This process can be triggered by various factors, including overcharging, physical damage, etc. To mitigate these risks, several strategies are employed, focusing on material selection, integration, and installation. Additionally, the safety assessment for lithium-ion batteries involves evaluating their compliance with international safety standards, which outline requirements for the safe operation of battery systems. Best practices in installation, operation, and maintenance are also considered to ensure long-term safety and reliability.

As mentioned above, thermal runaway is the main safety hazards of a Li-ion BESS. Thermal runaway is a process, which can be encountered at any time in the life of a Li-ion battery (from cell's production to recycling), whether the battery is in operation or not. It is an accelerated self-supporting rapid temperature increase mechanism that leads to destruction of the battery. This process can start at a relative low temperature when the lithium-ion cell reaches an internal temperature of around 70°C and lead to the next steps due to the exothermicity of the reactions [2]. If the heat produced during the different exothermic reactions cannot be dissipated, the cell's temperature will increase rapidly. This rising temperature will accelerate those exothermic reactions, producing even more heat and resulting in thermal runaway. A fire can be produced at a certain stage even without oxygen around the battery as the reactions create oxygen as byproduct of cell's decomposition.

H. Integration and installation

Every site is specific and has its own requirements which can impact the general safety, risks & mitigation methods. In order to be able to operate safely an

installation, it is of utmost importance that a HAZard IDentification (HAZID) workshop is conducted.

The goal of a HAZID study is to identify the site-specific potential hazards, their consequences without protections and determine potential safeguards to prevent, control or mitigate the risks locally. The safety experts from site owner, the operator and the supplier must perform this risk assessment closely together.

In practice, a HAZID workshop is axed around 7 main topics and their respective subdivisions involving all the safety technical actors in the project. This should be led by a HAZID expert as the idea is that no stone is left unturned and that all potential source of hazard has been covered, taking into consideration the existing as well as the upcoming.

Each hazard specific to the asset, the site and the project is identified and introduced in a risk matrix. This matrix helps to identify deviations with significant consequences by weighing the severity of each of them against their probability to determine the residual risk. The residual risks classified as unacceptable are then attributed to a single specific stakeholder and each get a dedicated action or safeguard measure. These safeguards encompass and can impact: the design of the installation (including the asset), the control systems, the procedures (e.g. installation, safety, Operation and Maintenance), and the personal protective equipment.

More specifically, one of the frequently underestimated and forgotten action in the industry is the early involvement of the fire brigade. For example, in our case study of FORWARD2030, the remoteness of the site and the time of intervention on site of the fire brigade had a strong impact on the BESS design and the site design in order to comply with the identified safety action as well as on the site safety procedures.

From experience, neglecting this early involvement, can heavily impact a project as it can, in extreme cases, result in a retrofit prior to installation as the proposed safety measure need to comply not only with local regulation but also with the specific requirements of the Authority Having Jurisdiction (AHJ) who has the last word even if in contradiction with the output of an HAZID.

I. Compliance with international safety standards and best practices

General guidelines, standards and practices are available on the market: Umbrella standards (e.g. UL 9540 & IEC 62933-5-1) and specific standards e.g. safety at system level, explosion and thermal runaway evaluation (e.g. NFPA855, FM Global 5-33, IEC 62933-3-2, UL9540A).

However, as the evolution of the market is constant and the limits of the new applicability of ESS is continuously pushed further (e.g. installed capacity, reduced safety distances, remoteness, floating structures), the standards are in constant improvement and evolution.

In order to take into account, not only the existing but also the upcoming evolutions, it is of utmost importance that an ESS Safety Expert - with practical knowledge and return of experience on both standard and technology - is involved in order to take into account not only the existing available rules and regulations but also the market evolution.

There are currently no guidelines on the vibrations sustainable by an ESS solution (at system level) in a stationary context. In our case study of FORWARD2030, our ESS Safety Expert was able to provide an indication of the thresholds that needed to be taken into consideration for floating structures. As these could not be respected with the selected BESS product available at that time (which took into consideration other project limitations and requirements), an ESS solution integrated in a floating structure, though interesting, was not retained as a solution.

V. CONCLUSION

The site location for FORWARD2030 is a remote test laboratory in a real environment designed. The installation of RES and ESS in remote areas with low grid hosting capacity presents significant challenges. The existing grid infrastructure for FORWARD2030, originally designed to supply energy to remote sites and communities, can however be used as a real test environment to evaluate and extrapolate the results to Large Scale Blue Economy projects (i.e. large-scale offshore renewable generation) with or without ESS.

The conditions at the FORWARD2030 site are ideal to test the limitations of remote operation, needed safety measures and associated requirements of an ESS in combination with RES. Remoteness, extreme weather conditions and distance to shore combined, are some of the most stringent conditions a stationary ESS could withstand. This pushed the limitations not only with respect to the selection of the technology but also the operation and last but definitely not least the safety practical measures and procedures. The learnings thereof will be applicable to large scale commercial Blue Economy projects combining and/or co-locating ESS with RES.

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