TWINVEST

Digital Twin for Forecasting of Power Production to Wind Energy Demand

Project title	Universal, open-source and cybersecure Digital Twin to provide investors in onshore wind farms valuable insights about current operations and future investments		
Project acronym	TWINVEST		
Project number	101146936		
Project start date	1 July 2024	**Duration**	42 months

D3.3 - ENERGY STORAGE ASSETS AND FLEXIBILITY

Due date	30/04/2025	Delivery date	06/05/2025
Work package	WP3		
Responsible Author(s)	ABEE RSTER		
Contributor(s)	Aanu Bajela (ABEE) Jose Maria Silva Corrugedo (ABEE) Foad Gandoman (RSTER) Vijay Mohan Nagulapati (RSTER)		
Reviewer(s)	RINA-C		
Version	V2.2		
Dissemination level	Public		

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

VERSION AND AMENDMENTS HISTORY

Version	Date (MM/DD/YYYY)	Created /Amended by	Changes
V0.1	14/03/2025	ABEE	Draft Version
V0.2	9/4/2025	RSTER/ABEE	Complete First Draft
V1.0	11/04/2025	RSTER/ABEE	Integration of Internal Review Comment
V1.1	28/04/2025	RINA-C	External Review
V1.2	28/04/2025	RSTER/ABEE	Integration of External Review Comments
V2.0	29/04/2025	RSTER/ABEE	Final version
V2.1	05/05/2025	ABEE	Final Version Updated
V2.2	05/05/2025	RINA-C	Final review

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

TABLE OF CONTENTS

TABLE OF CONTENTS 3
LIST OF FIGURES 4
LIST OF TABLES 4
LIST OF ABBREVIATIONS 5
1 INTRODUCTION 6
2 ELECTRICITY STORAGE 6
  2.1 STORAGE TECHNOLOGIES 6
  2.2 HIGH ENERGY BATTERIES 9
  2.3 HIGH POWER BATTERIES 11
  2.4 2^{ND} LIFE BATTERIES 12
  2.5 INNOVATIVE STORAGE TECHNOLOGY 13
3 BATTERY ENERGY STROAGE SYSTEM LIFE CYCLE COST 14
  3.1 CAPITAL EXPENDITURE (CAPEX) 15
  3.2 OPERATIONAL EXPENDITURE (OPEX) 16
  3.3 DECOMMISSIONING AND END-OF-LIFE (EOL) COSTS 17
  3.4 DEVELOPMENT AND INTEGRATION OF THE BESS LIBRARY INTO THE TWINVEST DIGITAL TWIN 17
4 SAFETY AND RELIABILITY ASSSESSMENT 19
  4.1 LIBRARY OF BATTERY SYSTEMS 19
  4.2 RELIABILITY AND SAFETY ASSESSMENT METHODOLOGY 20
    4.2.1 IEC 62620: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes –Secondary Lithium Cells and Batteries For Use In Industrial Applications 20
      4.2.1.1 Markings 21
      4.2.1.2 Battery designation 21
      4.2.1.3 Battery structural formulation 21
      4.2.1.4 Battery performance assessment 22
    4.2.2 IEC 62485-5: Safety Requirements for Secondary Batteries and Battery Installations – Part 5: Safe operation of stationary lithium-ion batteries 23
5 CONCLUSION 25
6 REFERENCES 26

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

LIST OF FIGURES

FIGURE 1: LITHIUM-ION BATTERIES 7
FIGURE 2: SODIUM-ION BATTERY 7
FIGURE 3: SUMITOMO ELECTRIC VANADIUM REDOX FLOW BATTERY 51 MWH PLANT IN HOKKAIDO, JAPAN 8
FIGURE 4: PUMPED HYDRO STORAGE FLOW TÂMEGA GIGABATTERY IN PORTUGAL 8
FIGURE 5: 100MW COMPRESSED AIR ENERGY STORAGE (CAES) IN ZHANGJIAKOU, HEBEI PROVINCE, CHINA 9
FIGURE 6: HYDROGEN FUEL GENERATION SYSTEM IN SHELL'S ENERGY AND CHEMICALS PARK RHEINLAND, GERMANY 9
FIGURE 7: NMC PRISMATIC CELL, 60 AH CAPACITY 10
FIGURE 8: COMPARISON BETWEEN NMC (RIGHT) AND LFP (LEFT) PRISMATIC CELLS. WHILE THE CAPACITY FOR LFP (113 AH) IS SLIGHTLY LESS THAN TWO TIMES THE NMC (60 AH), THE VOLUME IS MORE THAN DOUBLE 11
FIGURE 9: SUMITOMO ELECTRIC VANADIUM REDOX FLOW BATTERY 51 MWH PLANT IN HOKKAIDO, JAPAN 14
FIGURE 10: BESS LIBRARY DECISION FLOWCHART 18

LIST OF TABLES

TABLE 1: LIST OF HIGH-ENERGY BESS COMMERCIALLY AVAILABLE SOLELY SUITABLE FOR NMC BATTERIES. 10
TABLE 2: LIST OF HIGH-POWER BESS COMMERCIALLY AVAILABLE SOLELY SUITABLE FOR LFP BATTERIES. 12
TABLE 3: LIST OF 2ND LIFE BESS THAT ARE COMMERCIALLY AVAILABLE 13
TABLE 4: CAPITAL EXPENDITURE (CAPEX) COST COMPONENTS FOR BESS 15
TABLE 5: BATTERY SYSTEMS GENERAL SPECIFICATIONS 20
TABLE 6: BATTERY SYSTEMS ASSESSMENT BASED ON IEC 62620 SPECIFICATIONS 22
TABLE 7: BATTERY SYSTEMS INSTALLATION SAFETY SPECIFICATIONS BASED ON IEC 62485-5 24

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
BMS	Battery Management System
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
DC	Direct Current
DT	Digital Twin
EIA	Environmental Impact Assessment
EoL	End of Life
EV	Electric Vehicle
IEC	International Electrotechnical Commission
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate
NCA	Nickel Cobalt Aluminium
NMC	Nickel Manganese Cobalt
OPEX	Operating Expenses
PCS	Power Conversion System
ROI	Return on Investment
VRFB	Vanadium Redox Flow Battery

1 INTRODUCTION

Energy storage systems are playing an increasingly critical role in harnessing the energy captured from renewable sources like wind farms. They ensure the stable and reliable supply of electricity from the farms despite the intermittent nature of the supply. By storing the excess energy generated during peak wind periods, they can provide energy during off peak periods, enhance efficiency and reliability, while providing grid stability and increasing the share of renewable energy available for use. TWINVEST intends to create the foundation of a universal open source and cybersecure Digital Twin (DT) that will represent the main trustable and collaborative environment for different stakeholders in onshore wind energy. To achieve this, commercially available energy storage technologies suitable for use in a wind farm are collated into an energy storage library in this deliverable. A benchmark to identify high-power and high-energy options, taking into cognizance their technical feasibility for use to ensure flexible range of operation was implemented. Alongside these, 2nd life batteries were included in the library, and considerations for preforming a Life Cycle Cost (LCC) analysis for when they adapted for use in wind farms.

2 ELECTRICITY STORAGE

As the European Union (EU) strives to achieve climate neutrality by 2050, transition of energy generation away from fossil-fuel based sources is necessitated. This energy transition requires systemic changes to how energy is produced, distributed, and consumed. In this transition towards the inclusion of more renewable energy into the energy mix, a key enabler is integration of energy storage systems. By decoupling the timing of energy generation from consumption, storage systems enhance the flexibility and resilience of energy networks.

Energy storage contributes to multiple policy objectives and supports the integration of renewables, sector coupling, grid stability, and thereby improving energy security of the union. It plays a central role in balancing supply and demand, providing ancillary services, deferring grid investments, and ensuring continuity of supply in both normal and emergency conditions. Energy storage is increasingly being integrated into grid operation strategies through digitalization and smart control systems.

2.1 Storage Technologies

Energy storage technologies play a crucial role in balancing energy supply and demand, enhancing grid stability, and integrating renewable energy sources such as wind and solar. These technologies can be categorized based on their underlying principles, including electrochemical, mechanical, thermal, and chemical storage.

Electrochemical storage, primarily in the form of batteries, is one of the most widely used technologies. Lithium-ion batteries dominate the market due to their high energy density, efficiency, and long cycle life. They are commonly used in grid storage and electric vehicles, although challenges such as high capital expenditure (CAPEX), thermal management, and raw material constraints persist. An example of a cylindrical li-ion battery is shown in Figure 1. Sodium-ion batteries, shown in Figure 2, are emerging as a promising alternative, offering lower material costs and enhanced safety, albeit with slightly lower energy density.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Figure 1: Lithium-ion Batteries

Figure 2: Sodium-ion Battery

Flow batteries, such as vanadium redox and zinc-bromine, are well-suited for long-duration storage applications as they experience minimal degradation over time. However, their lower energy density limits their use in high-power applications. Sumitomo Electric Vanadium Redox Flow Battery 51 MWh plant in Hokkaido, Japan in Figure 3 is an example of this technology in use. Lead-acid batteries, while cost-effective, suffer from short lifespans and lower efficiency, making them more suitable for backup power. Solid-state batteries, considered the next generation of electrochemical storage, promise higher energy density and improved safety, though they are still in the early stages of commercialization.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Figure 3: Sumitomo Electric Vanadium Redox Flow Battery 51 MWh plant in Hokkaido, Japan

Mechanical energy storage technologies rely on the conversion of electrical energy into kinetic or potential energy. Pumped hydro storage is the most established form, involving the movement of water between reservoirs at different elevations to store and generate electricity. It boasts high efficiency and a long operational lifespan of over 50 years, but it is highly dependent on suitable geography. An example is the Tamega Gigabattery project in Portugal shown in Figure 4 (Iberdrola, 2022).

Figure 4: Pumped Hydro Storage Flow Tâmega Gigabattery in Portugal

Compressed air energy storage functions by compressing air into underground caverns and later expanding it to drive turbines, making it ideal for large-scale storage. However, the requirement for specific geological formations poses a limitation. An example of this is the 100MW compressed air energy storage system in Zhangjiakou, China shown below in Figure 5.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Figure 5: 100MW Compressed Air Energy Storage (CAES) in Zhangjiakou, Hebei Province, China

Chemical storage involves converting electricity into chemical bonds for later use. Hydrogen storage is a prominent example, where electricity is used to produce hydrogen through electrolysis, which can then be stored and utilized in fuel cells, grid storage, or industrial applications. However, its low round-trip efficiency, and the need for specialized infrastructure remain key challenges. The largest Proton Exchange Membrane (PEM) as of 2021 was commissioned by Shell Energy and Chemicals in Rheinland, Germany with a production capacity of 10MW shown in Figure 6 (Shell, 2021).

Figure 6: Hydrogen Fuel Generation System in Shell's Energy and Chemicals Park Rheinland, Germany

While the options for storing energy are diverse, this document will focus on the use of lithium-ion batteries as the primary option to satisfy the needs of wind farms and power grids all over the European territory.

2.2 High Energy Batteries

High-energy lithium-ion batteries are a category of lithium-ion batteries designed to maximize energy density, making them ideal for applications requiring extended operational time and high energy storage capacity. These batteries are widely used in electric vehicles, grid storage, and portable electronics due to their ability to store more energy per unit of weight and volume compared to standard lithium-ion batteries.

The performance of high-energy Li-ion batteries is largely influenced by the choice of electrode materials. The cathode, which is a crucial component in determining energy density, typically consists

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

of materials like nickel-rich lithium nickel manganese cobalt oxide (NMC) or lithium nickel cobalt aluminium oxide (NCA). These materials offer a higher specific capacity compared to traditional lithium iron phosphate (LFP) cathodes. A common commercial NMC prismatic cell can be seen in Figure 7.

Figure 7: NMC prismatic cell, 60 Ah Capacity

Due to the nature of NMC cells of having a high energy density, they became a good match for renewable energy storage, since a higher energy density can be translated into a lower carbon footprint. In addition, this type of cell chemistry can adapt in a flexible way to the dynamic behaviour of energy demand from power grids.

Within the scope of the TWINVEST project, a library of commercially available energy storage assets suited for wind farms applications was created. This library is included into the framework investment conditions platform, one of the five platforms that compose the Digital Twin to be developed as part of this project. The list of High Energy Battery Energy Storage System (BESS) for the energy storage assets can be seen in Table 1. Note that all the equipment found in the table are suitable for operation using only NMC batteries.

Table 1: List of high-energy BESS commercially available solely suitable for NMC batteries.

Manufacturers	**Model**	**Capacity (kWh)**
MTU	Energypack_QS 400/6	625
MTU	Energypack_QS 400/4	416
MTU	Energypack_QS 200/3	312
MTU	EnergyPack QL	2200

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

2.3 High Power Batteries

High-power lithium-ion batteries are designed to deliver energy quickly, providing high power output while maintaining efficiency and durability. Unlike high-energy Li-ion batteries which prioritize maximizing energy density for extended use, high-power Li-ion batteries focus on rapid charge and discharge capabilities, making them ideal for applications requiring bursts of power. These applications include electric vehicles with regenerative braking, power tools, hybrid electric vehicles, and grid applications requiring fast response times.

The primary difference between high-power and high-energy Li-ion batteries lies in their electrode materials and overall design. In high-power batteries, the cathode material is often lithium iron phosphate (LFP), which offers excellent thermal stability and long lifecycle, making it particularly suitable for demanding applications where safety and longevity are critical.

The anode in high-power Li-ion batteries is typically made of graphite, though alternative materials like lithium titanate (LTO) are used for even faster charge-discharge rates and improved cycle life. LTO anodes allow for extremely fast charging, often within minutes, and provide exceptional durability, with cycle life extending beyond 10,000 cycles. However, the trade-off is lower energy density compared to graphite-based anodes, which means that while the battery can deliver high bursts of power, it does not store as much total energy per unit weight or volume. A comparison between the size of NMC and LFP cells, highlighting the energy density difference can be seen in Figure 8.

Figure 8: Comparison between NMC (right) and LFP (left) prismatic cells. While the capacity for LFP (113 Ah) is slightly less than two times the NMC (60 Ah), the volume is more than double.

One of the key characteristics of high-power li-ion batteries is their low internal resistance, which minimizes heat generation and allows for rapid energy transfer. The lower resistance also contributes to greater efficiency, reducing energy losses and improving overall performance. Despite their advantages, high-power Li-ion batteries face certain challenges. The lower energy density compared to high-energy variants means they are not always the best choice for applications requiring long runtimes. Additionally, frequent high-power cycling can lead to faster degradation if not properly managed. Table 2 lists the high-power BESS commercially available. Note that all the equipment included in the library is suitable for operation only with LFP batteries.

Table 2: List of high-power BESS commercially available solely suitable for LFP batteries.

Manufacturer	Model	Capacity [kWh]
Greensun	GS500KWH-LFP	500
Greensun	GS800KWH-LFP	800
Greensun	GS1MWH-LFP	1000
Ampowr	AF-C10-CY-425-NCPB-200	425
Ampowr	AF-C10-CY-1100-NCPB-500	1100
Ampowr	AF-C20-CY-2060-NCPB-1000	2060
Ampowr	AF-4LC	4000
Ampowr	AF-2.5-5LC	5000
Tesla	Megapack	2529
Tesla	Megapack 2	3854
Tesla	Megapack 2 XL	3916

2.4 2nd Life Batteries

Second-life lithium-ion batteries refer to used batteries repurposed for applications beyond their original use, primarily from electric vehicles. While a battery may no longer meet the stringent performance requirements of an EV, after its state of health drops below 80%, it can still provide valuable energy storage for less demanding applications. Repurposing these batteries extends their lifespan, improves sustainability, while reducing the environmental impact of battery disposal.

One of the most promising applications for second-life batteries is stationary energy storage, where they are used in grid stabilization, renewable energy integration, and backup power systems. Since grid storage does not require the high power and rapid cycling of EV batteries, used batteries can still provide reliable service for years. In particular, they are useful in renewable energy storage, allowing wind and solar farms to store excess energy and release it when needed.

While second-life batteries offer significant advantages, they also present challenges. One of the main issues is battery degradation and variability. Each battery has experienced different usage patterns, temperatures, and charge/discharge cycles, leading to inconsistencies in remaining capacity and performance. This heterogeneity complicates the processes of testing, sorting, and repurposing at scale, as uniform performance cannot be assumed across battery modules. The absence of standardized data on battery history and state-of-health also limits the ability to accurately assess suitability for second-life applications.

Another challenge is safety and regulatory compliance. Aging batteries may have a higher risk of failure and/or thermal runaway, requiring advanced battery management systems (BMS) and thermal management solutions. Ensuring compliance with existing transport, handling, and storage regulations across multiple jurisdictions adds complexity to second-life battery deployment. Harmonized standards for testing, labelling, and end-of-life handling are still under development, creating uncertainty for manufacturers and system integrators.

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

For the BESS assets library, 2nd life batteries that are commercially available was also included. As this market is expanding, and with the current increase in the usage of EVs, the rate of available 2nd life batteries will grow rapidly. However, as previously mentioned, safety and standardization remain an issue for this type of product; thus, despite being included in the library for the framework conditions investment platform, they will not be given priority over BESS using fresh batteries.

The list of BESS using 2nd life batteries can be seen in Table 3.

Table 3: List of 2nd life BESS that are commercially available

Manufacturer	Model	Capacity [kWh]
WATT4EVER	PowerCab100	100
WATT4EVER	PowerCab200	200
WATT4EVER	PowerCab300-1PCS	300
WATT4EVER	PowerCab300-2PCS	300
WATT4EVER	PowerCab400-1PCS	400
WATT4EVER	PowerCab400-2PCS	400

2.5 Innovative Storage Technology

Although lithium-ion batteries are currently one of the main options regarding the storage of energy, they did not reach this place by casualty. Other type of batteries, such as lead acid, where the main choice, until the continuous development and improvement of Li-ion cells performance reached a competitive stage and started becoming the preferred option instead formerly mentioned technology.

With the purpose of highlighting promising technologies that can reach a status of a widely spread commercial product, in this report innovative energy storage technologies were mentioned, although not included in the library as their adoption level is still being limited by factors such as costs and efficiency.

From several storage technologies under development, one that have gained attention and proven a rapid grow are the flow batteries. Flow batteries are a type of rechargeable battery designed for large-scale energy storage applications. Unlike conventional lithium-ion batteries, which store energy in solid electrodes, flow batteries store energy in liquid electrolytes that circulate through an electrochemical cell.

As with every technology aimed to be implemented at industrial scale, steps such as lab scale prototypes to pilot plants, must be taken to demonstrate the successful integration to the current systems without affecting the daily activities of the end users. In the case of flow batteries, several case studies at large scales are ongoing. One tangible example is in Japan, where Sumitomo Electric together with Hokkaido Electric Power Company have introduced a large-scale storage system at the Minami-Hayakita Substation. This system utilizes Vanadium Redox Flow Battery (VRFB) technology, supporting the grid stabilization and smoothing fluctuations in power generation.

The VRFB system, with a capacity of 51 MWh was established in April 2022, representing one of the world's biggest facilities in operation with this technology (Sumitomo, 2022). 21 years of continuous operation are required to ensure ongoing stability and support for the integration of renewable energy into the grid. A picture of the system installed in Hokkaido can be seen in Figure 9.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Figure 9: Sumitomo Electric Vanadium Redox Flow Battery 51 MWh plant in Hokkaido, Japan

3 BATTERY ENERGY STROAGE SYSTEM LIFE CYCLE COST

The BESS typically consists of the battery system, a power conversion system (PCS), connected to the grid through a switchgear and a transformer. The battery system is made up of the battery cells, containing racks and a battery monitoring system (BMS) to ensure all the composite cells of the battery pack is functioning optimally. The power conversion system consists of inverters to charge and discharge the batteries and to convert from direct current (DC) from the batteries to alternating current (AC) to the grid. The associated cost of all these components and accompanying consumables extends beyond the initial procurement period but till the decommissioning and disposal/recycle phase (Alaperä, Honkapuro, Tikka, & Paananen, 2019)

Life Cycle Cost (LCC) is a cost analysis technique used to estimate the economic long-term viability of a project. It is used to identify, analyze, and forecast the total cost associated with the project. Evaluating the life cycle cost (LCC) of BESS is crucial for informed decision-making, optimization of returns of investment (ROI) and to ensure economic viability of projects. The LCC analysis should covers all costs associated with the BESS over its entire lifecycle, including all initial capital expenditure (CAPEX), operational and maintenance expenses (OPEX), end-of-life (EoL) and decommissioning costs (Shafiee, Brennan, & Espinosa, 2016).

$$\mathbf{LCC = \sum (C_{CAPEX} + C_{OPEX} + C_{EoL})}$$

Where:
C_{CAPEX} - Total capital expenditure
C_{OPEX} - Total operations expenditure
C_{EOL} - Total end of life expenditure

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

3.1 Capital Expenditure (CAPEX)

The system CAPEX which includes components such as expenses related to the project management, permitting, engineering design, site preparation, procurement and installation of battery systems, power conversion systems, and balance of plant components represents the largest component of the LCC. In the Table 4 below, each component to be considered in the calculation of the CAPEX is itemized (NREL, 2023) (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022).

Table 4: Capital Expenditure (CAPEX) Cost Components for BESS

Component	Description	Typical Share of CAPEX (%)
Battery Pack (Cells & Modules)	Energy storage medium (e.g., Li-ion, VRFB)	35–45%
Power Conversion System (PCS)	Inverters/converters for AC/DC integration	10–20%
Battery Management System (BMS)	Monitors voltage, temperature, SOC, safety	3–7%
Thermal Management System	HVAC, liquid cooling or air systems to maintain temperature	3–8%
Balance of Plant (BoP)	Wiring, switchgear, transformers, cabling, mounting structures	10–15%
Control and Communication System	SCADA, energy management system (EMS), communication interfaces	2–5%
Civil and Site Works	Site preparation, foundations, access roads, fencing	5–10%
Engineering, Procurement, Construction (EPC)	Design, engineering, project management, and commissioning	5–10%

The total CAPEX can be expressed as:

$$C_{CAPEX} = C_{bat} + C_{pcs} + C_{BMS} + C_{BoP} + C_{thermal} + C_{contr} + C_{civil} + C_{epc}$$

Where:

C_{bat} - Cost of battery cells and modules
C_{pcs} - Cost of power conversion system
C_{BMS} - Cost of battery management system
C_{BoP} - Cost of balance of plant
$C_{thermal}$ - Cost of thermal management system
C_{contr} – Cost of control system
C_{civil} - Cost of civil works and site preparation
C_{epc} - Cost of engineering, procurement, and construction

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

3.2 Operational Expenditure (OPEX)

The OPEX comprises of the ongoing costs associated with the operating, monitoring, component replacements, and maintenance of the BESS throughout its functional lifecycle. The distribution of these OPEX components will vary based on certain factors including system size, technology type, operational environment, and usage patterns. For instance, systems deployed in harsh climatic conditions may incur higher thermal management costs, while those in regions with stringent regulatory frameworks might face higher compliance expenses (Hanawalt, Eyman, Corbitt, & Kim, 2021) (NREL, 2023) (Yildiz, Hemida, & Baniotopoulos, 2024). The factors to be considered in calculating the OPEX include:

1. **Routine Maintenance and Repairs:** This is divided into 2 main categories which are preventive and corrective maintenance. Preventive maintenance is the regular inspection and servicing of components of the BESS, thereby ensuring the optimal performance and the prevention of unexpected failures and downtimes. This includes tasks like firmware updates, cleaning, and tightening of electrical connections. Corrective maintenance addresses unforeseen malfunctions or component failures that require immediate attention to restore system functionality. This might involve the replacement or repairing of defective or damaged parts and components
2. **Battery Augmentation and Replacements:** Over time, the cells of batteries begin to degrade, leading to a reduction in capacity and efficiency. To maintain the desired performance levels, it usually necessary to augment the system by replacing degraded ones and adding new battery modules. This cost is the aggregate of the procurement cost of the new batteries, the disposal cost of the used ones, including the logistics and labour cost of integration.
3. **Auxiliary Systems:** BESS installations often require auxiliary systems such as thermal management (cooling or heating) and control systems to operate continuously. These systems consume energy which adds to the operational costs.
4. **Insurance and Warranty Expenses:** Securing insurance coverage for a BESS is essential to mitigate risks associated with equipment damage, operational liabilities, and other unforeseen events. Also, extending warranties and service agreements with manufacturers can provide coverage for certain repairs and replacements, impacting the overall OPEX.
5. **Labor and Administrative Costs:** Administrative expenses include training, documentation, and stakeholder communications. The labour costs consist of remunerations paid to skilled personnel for tasks such as system maintenance, monitoring, data analysis, reporting, and compliance with safety and environmental regulations.
6. **Regulatory Compliance and Environmental Management:** The costs of conducting periodic environmental impact assessment (EIA), safety audits, and obtaining and sustaining necessary operation permits are also important to be considered in the calculation of the OPEX. Also to be considered is the cost of implementation of environmental management practices, such as proper disposal of replaced components, contributes to sustainable operations.

$$\mathbf{C_{OPEX} = C_{main} + C_{arg/rep} + C_{anc} + C_{ins} + C_{admin} + C_{compliance}}$$

Where:
C_{main} – Cost of Maintenance and Repairs
$C_{arg/rep}$ – Cost of Battery Augmentation and Replacements
C_{anc} – Cost of Auxiliary Systems

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

C_{ins} - Cost of Insurance and Warranty
C_{admin} – Cost of Administrative
$C_{compliance}$ - Cost of Regulatory Compliance and Environmental Management

3.3 Decommissioning and End-of-Life (EoL) Costs

At the end of its operational life, the BESS incurs several costs related to decommissioning and appropriate end-of-life (EoL) management. They include:

1. **Decommissioning and Dismantling:** This includes the cost of labour and equipment required to safely disconnect, dismantle, and remove the BESS and its ancillary services from the site. This also includes the cost of restoring the site to its original condition or preparation for next use.
2. **Transportation:** This accounts for the cost of transporting decommissioned batteries and components to recycling or disposal facilities. The cost varies based on distance, transportation mode, and the need for specialized handling due to the hazardous nature of battery materials.
3. **Recycling and Disposal:** This is the cost incurred in extracting valuable materials such as lithium, cobalt, and nickel from spent batteries. Other expenses covered by this component are those related to the safe disposal of non-recyclable components in compliance with environmental regulations to prevent pollution.
4. **Regulatory Compliance:** This refers to the costs associated with obtaining necessary permits and completing required documentation for decommissioning and transportation of waste. This also includes the cost of conducting necessary EIA in compliance with regulations.

$$\mathbf{C_{EoL} = C_{decom} + C_{transport} + C_{rec} + C_{compliance}}$$

Where:
C_{decom} – Cost of decommissioning and dismantling
$C_{transport}$ – Cost of transportation
C_{rec} – Cost of recycling and disposal
$C_{compliance}$ – Cost of regulatory compliance

3.4 Development and Integration of the BESS Library into the TWINVEST Digital Twin

The battery energy storage library developed to support the planning and optimization of energy storage systems within onshore wind farm projects is to be used as a tool integrated into the framework investment conditions platform. It will serve as a decision-making aid for investors evaluating the technical and financial viability of wind farm developments when a BESS is incorporated. This library captures a range of BESS solutions segmented by battery chemistry, either high-energy (NMC) or high power (LFP), and second-life battery.

The library was developed using a phased, standards-driven approach:

Phase 1 - Data Collection: sourced technical specifications from manufacturers (e.g., MTU, Tesla, Greensun), regulatory standards (IEC 62620, IEC 62485-5), and existing market information.

Phase 2 - Structuring: prioritized the available BESS options, separating LFP, NMC, and 2nd-life technologies into updatable sub-libraries, adapting to market trends. Innovative solutions options such as VRBFs were not included in the library as they are still not commercially developed solutions.

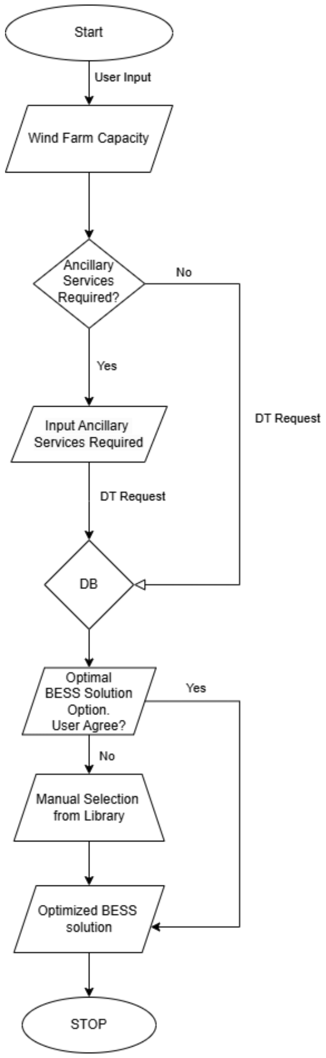
Funded by the European Union

Funded by the European Union, under Grant Agreement Nº 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Phase 3 – Validation: compliance checks were done applying IEC 62620 for performance thresholds, and IEC 62485-5 for safety.

Finally, the library generates outputs of pre-filtered BESS options with forecasted financial projections (CAPEX, OPEX, EoL costs), enabling stakeholders to prioritize solutions based on technical feasibility, regulatory adherence, and financial considerations. Below in Figure 10 is a process flowchart showing the library operation process. This flow chart is an initial approach to how the database will integrate and function in the DT. The definitive logic of the functionality of the flow chart will be described in details once the complete DT architecture is established. This will be explored in Work Package 2.

Figure 10: BESS Library Decision Flowchart



The BESS library interfaces dynamically with the DT through standardized data exchange protocols such as RESTful APIs which transmit information such as system sizes of the listed options, electrochemical configuration (LFP, NMC, 2nd Life LFPs), manufacturer, forecasted CAPEX, OPEX, and EoL data, allowing real-time financial modelling for the wind farm with the BESS inclusive. With this output data, the library supports the various DT platforms with the required database with which it can enable investor to better approach project decision making.

4 SAFETY AND RELIABILITY ASSSESSMENT

Energy storage systems (ESS) play a critical role in ensuring the stability and reliability of wind farms by balancing intermittent energy production and supporting grid stability. Effective deployment of ESS requires comprehensive evaluation of their reliability and safety, particularly under the demanding operational conditions associated with wind energy applications. As part of the TWINVEST project, a comprehensive battery system library has been prepared to support the integration of wind energy into power grids. The library encompasses diverse battery technologies and configurations intended for high-power, high-energy, and second-life applications. To ensure optimal safety and reliability in wind energy storage contexts, all battery systems in the library were rigorously assessed against international standards—IEC 62620 and IEC 62485-5.

The IEC 62620 standard specifies performance and reliability requirements for secondary lithium-ion cells and batteries, focusing on energy capacity, cycle life, and thermal performance. On the other hand, the IEC 62485-5 standard outlines safety measures for battery systems in stationary applications, addressing electrical protection, fire resistance, and thermal management. Compliance with these standards is essential to minimize operational risks, enhance energy storage reliability, and ensure the safety of personnel and infrastructure.

This section provides an in-depth assessment of the reliability and safety of various battery energy storage technologies deployed in wind farms. It evaluates key parameters such as performance under dynamic loading conditions, resilience to environmental factors, fault management capabilities, and adherence to regulatory requirements. By applying the guidelines of IEC 62620 and IEC 62485-5, the analysis aims to identify best practices for safe and efficient battery system integration within wind farm operations.

The scope of this assessment includes performance evaluation (capacity, efficiency, cycle life) as per IEC 62620. Safety and risk assessment (thermal stability, electrical protection, mechanical integrity) as per IEC 62485-5. The findings from this assessment will support stakeholders in making informed decisions on battery selection, maintenance strategies, and safety management, contributing to the overall sustainability and resilience of wind energy systems.

4.1 Library of Battery Systems

The battery system library was curated to reflect a broad representation of technologies currently deployed or under development for renewable energy storage. Battery systems were categorized as

- **High Power (LFP)**: suitable for applications requiring high current and robust thermal stability. ex. Greensun, Ampowr
- **High Energy (NMC)**: Suitable for long duration storage with high energy density. ex. Aggreko
- **Second life batteries**: Recycled or refurbished batteries from earlier deployments, suitable for cost sensitive and sustainable applications.
  ex. Watt4ever

The technical specifications and manufacturer provided data for the selected battery systems are compiled and are presented in

Table 5.

Table 5: Battery systems general specifications

Battery system/General specifications	Manufacturer Name	Battery Model	Battery Type	Nominal Voltage (V)	Rated Capacity (Ah)	Rated Energy (Wh)	Weight (kg)	Dimensions (LxWxH in mm)
High Power (LFP)								
AF-C10-CY-425-NCPB-200	AMPOWER	AF-C10-CY-425-NCPB-200	LFP	768	215.04 kWh	425 kWh	11 t	2991 × 2591 × 2438
GS500KWH-LFP (Greensun)	Greensun	GRS-500/1000-EU	LFP	716.8	1400 kWh	1003.52 kWh	1860 kg	6058 × 2438 × 2591
AF-4LC (Ampowr)	AMPOWER	AF-4LC	LFP	1331.2	280/300 kWh	4 MWh	36 t	6258 × 2488 × 2896
AF-2.5-5LC (Ampowr)	AMPOWER	AF-2.5-5LC	LFP	1331.2	314 kWh	5 MWh	43 t	6258 × 2488 × 2896
High Energy (NMC)								
Energy pack QS	Rolls-Royce	QS 400/6	NMC	400	625 kWh		10.5 t	3300 × 2220 ×2530
Energy pack QS	Rolls-Royce	QS 400/4	NMC	400	416 kWh		9.1 t	3300 × 2220 ×2530
Energy pack QS	Rolls-Royce	QS 200/4	NMC	400	416 kWh		9.1 t	3300 × 2220 ×2530
Energy pack QS	Rolls-Royce	QS 200/3	NMC	400	312 kWh		8.4 t	3300 × 2220 ×2530
Second Life Batteries								
PowerCab100 (WATT4EVER)	WATT4EVER	PowerCab 100	Li-ion			100 kWh	950 kg	1200 × 1210 × 2100
PowerCab200 (WATT4EVER)	WATT4EVER	PowerCab 200	Li-ion			200 kWh	1750 kg	1200 × 2010 × 2100
PowerCab300-1PCS (WATT4EVER)	WATT4EVER	PowerCab 300-1PCS	Li-ion			300 kWh	2500 kg	1200 × 2810 × 2100
PowerCab300-2PCS (WATT4EVER)	WATT4EVER	PowerCab 300-2PCS	Li-ion			300 kWh	2600 kg	1200 × 3220 × 2100
PowerCab400-1PCS (WATT4EVER)	WATT4EVER	PowerCab 400-1PCS	Li-ion			400 kWh	3300 kg	1200 × 3610 × 2100
PowerCab400-2PCS (WATT4EVER)	WATT4EVER	PowerCab 400-2PCS	Li-ion			400 kWh	3400 kg	1200 × 4020 × 2100

4.2 Reliability and Safety Assessment Methodology

The battery systems were evaluated based on IEC 62620 and IEC 62485-5 standards. Each battery system was assessed against a matrix of specifications derived from the two IEC standards.

4.2.1 IEC 62620: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Secondary Lithium Cells and Batteries For Use In Industrial Applications

This international standard specifies requirements with respect to markings, tests and requirements for lithium secondary cells and batteries used in industrial applications including stationary applications (Standards, 2020). The specifications range from markings and designation, structural formulation and performance details.

4.2.1.1 Markings

Each cell or battery system installed should clearly have these markings giving the information. The following options are allowed:

- If markings are present on the battery system, it is not necessary to mark the battery pack, module, or cell
- If markings are present on the battery pack, it is not necessary to mark the module or cell
- If markings are present on the module, it is not necessary to mark the cell

Each cell or battery that is installed or maintained must carry legible and durable markings that include:

- Identification as secondary (rechargeable) Li or Li-ion
- Polarity (this may be omitted if agreed upon by both the cell and pack manufacturers)
- Date of manufacture (can be encoded)
- Name or identification of the manufacturer or supplier
- Rated capacity
- Nominal voltage
- A relevant caution statement

Additionally, the following information must be either marked on or supplied with the cell or battery:

- Disposal instructions
- Recommended charging instructions

4.2.1.2 Battery designation

Batteries shall be designated with following form:

Battery structural formulation

$$A_1A_2A_3N_2/N_3/N_4[S_1]A_4/T_LT_H/N_C$$

A_1 designates the negative electrode

A_2 designates the positive electrode

A_3 designates the shape of the cell

A_4 designates the rate capability of the battery in which

T_L Low temperature grade

T_H High temperature grade

Nc Percentage ratio of capacity at 500 cycles to the rated capacity

N_2 Maximum diameter

N_3 Maximum width

N_4 Maximum height

4.2.1.3 Battery structural formulation

The battery designation should include the structural formulation of the battery starting from the smallest unit to the largest one and their connection details like number of series and parallel connections.

Funded by
the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

4.2.1.4 Battery performance assessment

The battery systems performance was assessed against a matrix of specifications derived from IEC 62620 standard as shown in Table 6.

Table 6: Battery systems assessment based on IEC 62620 specifications

		High power			**High Energy**				**Second life battery**					
Specification	AF-C10-CY-425-NCPB-200	GS500KWH-LFP (Greensun)	AF-4LC (Ampowr)	AF-2.5-5LC (Ampowr)	Energy pack QS 400/6 (RR)	Energy pack QS 400/4 (RR)	Energy pack QS 200/4 (RR)	Energy pack QS 200/3 (RR)	PowerCab 100 (WATT4EVER)	PowerCab 200 (WATT4EVER)	PowerCab 300-1PCS (WATT4EVER)	PowerCab 300-2PCS (WATT4EVER)	PowerCab400-1PCS (WATT4EVER)	PowerCab 400-2PCS (WATT4EVER)
Nominal Voltage (V)	786	716.8	1331.2	1331.2	400	400	400	400	400	400	400	400	400	400
Nominal Capacity (Ah)	280 Ah	1400	280/300 Ah	314Ah	625 kWh	416 kWh	416 kWh	312 kWh	-	-	-	-	-	-
Energy Density (Wh/kg) >100 Wh/kg	425 kWh	1003.52 kWh	4 MWh	5 MWh					100 kWh	200 kWh	300 kWh	300 kWh	400 kWh	400 kWh
Cycle Life (cycles) >2000 cycles @ 80% DOD	5000	6000	8000	8000					-	-	-	-	-	-
Self-Discharge Rate <5%/month)	-	-	-						-	-	-	-	-	-
Overcharge Tolerance (V)	-	Yes							-	-	-	-	-	-
Thermal Runaway		-			-	-	-	-	-	-	-	-	-	-

Funded by the European Union

Funded by the European Union, under Grant Agreement Nº 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

Temp (>150°C°C)														
Short Circuit Protection		-			17 kA	17 kA	17 kA	17 kA	-	-	-	-	-	-
Operating Temperature Range (-20 to 60°C)	-20 to 40	-10 to 50	-30 to 55	-30 to 55	-20 to 45/50	-20 to 45/50	-20 to 45/50	-20 to 45/50	-20 to 55	-20 to 55	-20 to 55	-20 to 55	-20 to 55	-20 to 55
Storage Temperature Range (-40 to 60°C)	-	-25 to 25	-20 to 45	-20 to 45	-	-	-	-	-	-	-	-	-	-
System formulation	1P240S	14S1P	1P416S ×10	1P416S ×12	-	-	-	-	1 string	2 strings	3 strings	3 strings	4 strings	4 strings
Markings	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Designation	Yes	Yes	Yes	Yes	-	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes
Weight	11 t	1860 kg	36 t	43 t	10.5 t	9.1 t	9.1 t	8.4 t	950 kg	1750 kg	2500 kg	2600 kg	3300 kg	3400 kg
Dimensions (LxWxH in mm)	2991× 2591 × 2438	6058 × 2438 × 2591	6258 × 2488 × 2896	6258 × 2488 × 2896	3300 × 2220 × 2530	3300 × 2220 × 2530	3300 × 2220 × 2530	3300 × 2220 × 2530	1200 × 1210 × 2100	1200 × 2010 × 2100	1200 × 2810 × 2100	1200 × 3220 × 2100	1200 × 3610 × 2100	1200 × 4020 × 2100
IEC 62620 Compliance	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No

4.2.2 IEC 62485-5: Safety Requirements for Secondary Batteries and Battery Installations – Part 5: Safe operation of stationary lithium-ion batteries

This international standard outlines the necessary precautions to mitigate risks related to electrical, fire, chemical, mechanical hazards, and ventilation (Standards, 2020). The standard aims to ensure the safe usage of stationary batteries across various settings. Part 5 of the standard applies to the installation of one or more stationary secondary batteries having a maximum aggregate DC voltage of 1500 V to any DC part of the power network and describes the principal measures for protections during normal operation or under expected fault conditions against hazards generated from electricity, short-circuits, electrolyte, gas emission, fire, and explosion. The recommendations summarized in Table 7 serve as essential considerations for planning and implementing robust and future proof stationary storage systems.

Table 7: Battery systems installation safety specifications based on IEC 62485-5

IEC 62485-5 specification	Recommendations
Disconnection and separation	Circuit breakers/ switches
Electrical separation	TN/TT/IT systems
Extra low voltage protection	SELV, PELV, FELV
Short-circuit protection	within 500 ms
Overcharge/over-discharge protection	Automatic disconnect at upper and lower limits of charging
Hazardous chemical release	Safety data sheet (SDS)of harmful chemicals that can be released
General Safety Requirements	Regular maintenance and inspection should be scheduled to ensure system integrity.
Ventilation	Adequate ventilation must be provided to prevent the accumulation of explosive gases.
Protection Against Electric Shock	Enclosures should be designed to prevent accidental contact with live parts.
Protection Against Hazards from Electrolyte	Use of acid-resistant trays or containers is recommended to contain any electrolyte spillage.
Fire Protection	Fire detection and suppression systems suitable for battery installations should be installed.
Marking and Labelling	All components and equipment should be clearly labelled with safety information.
Installation Requirements	Batteries must be installed according to manufacturer guidelines and national regulations.
Accessibility	Equipment should be easily accessible for maintenance and emergency intervention.
Connection and Interconnection	All electrical connections must be mechanically secure and electrically reliable.
Earthing and Bonding	Proper earthing should be implemented to reduce the risk of electric shock.
Operational Safety	Personnel should be trained in the correct handling and operation of battery systems.
Maintenance	Maintenance should be carried out by qualified personnel using appropriate tools and PPE.
Emergency Procedures	Clear and well-communicated emergency plans should be established.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

5 CONCLUSION

The transition toward a decarbonized and resilient energy grid in Europe demands efficient, scalable, and safe energy storage systems that can support renewable generation from sources like wind energy farms. This deliverable has explored and collated commercially available storage technologies, assessed their suitability for wind farm applications, and provided a structured framework for their evaluation within the TWINVEST Digital Twin platform.

The technical and economic analysis of the BESS play a critical role is enabling investors make well informed decision. The library developed consists of high-energy batteries for extended duration storage and high-power batteries for rapid response applications. Complimentary to these, 2nd life batteries were analyzed; considering the growing availability of used up EV batteries in the market as EV adoption increases, although current regulatory and technical limitations warrant careful consideration in deployment. Innovative solutions including VRFB batteries were also explored. These commercially available systems were curated into the library based on performance, lifecycle cost, and safety criteria.

The life cycle cost analysis presented offers a granular view of the investment required for the full operational lifetime of a BESS; from CAPEX associated with procurement and installation, through the OPEX related to maintenance and performance management, to end-of-life costs involving decommissioning, and recycling. This framework will enable investors and system operators to make financially informed decisions that also reflect long-term sustainability targets.

This assessment framework also ensures that the battery library aligns with industry standards, supporting safe and efficient energy storage system deployment. Through systemic assessment using IEC 62620 and IEC 62485-5 standards, each system was evaluated for safety and reliability ensuring efficient wind energy storage for an enhanced renewable energy infrastructure.

By integrating these technologies and evaluation frameworks into the TWINVEST Digital Twin platform, the deliverable lays a solid foundation for dynamic, real-time insights that can guide stakeholder decisions across the lifecycle of onshore wind assets. The findings of this report confirm that flexible energy storage hedged by standardized safety protocols and comprehensive cost analysis is important to unlocking even more possibilities and adaptability of onshore wind farms.

Funded by the European Union

Funded by the European Union, under Grant Agreement N° 101146936. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or RIA. Neither the European Union nor the granting authority can be held responsible for them.

6 REFERENCES

Alaperä, I., Honkapuro, S., Tikka, V., & Paananen, J. (2019). Dual-purposing UPS batteries for energy storage functions: A business case analysis. *Energy Procedia*, 158. doi:https://doi.org/10.1016/j.egypro.2019.01.645

Hanawalt, S., Eyman, M., Corbitt, J., & Kim, K. (2021). What Operators Needs to Know About BESS Information Gaps. Retrieved from https://www.powerfactors.com/blog/energy-storage-info-gap

Iberdrola. (2022). Iberdrola inaugurates 40GWh Tamega pumped hydro plant in Portugal. *247 Energy Storage*, 20. Retrieved from https://247storage.energy/iberdrola-inaugurates-40gwh-tamega-pumped-hydro-plant-in-portugal/

NREL. (2023). *Utility-Scale Battery Storage*. Retrieved from public.tableau.com: https://public.tableau.com/views/2024CMTS/TechSummary?:embed=y&:toolbar=no&Technology=Utility-Scale%20Battery%20Storage&Core%20Metric%20Parameter=CAPEX,Fixed%20O%26M,Variable%20O%26M,OCC&:embed=y&:showVizHome=n&:bootstrapWhenNotified=y&:apiID=handler0

Shafiee, M., Brennan, F., & Espinosa, I. (2016). A parametric whole life cost model for offshore wind farms. *The International Journal of Life Cycle Assessment*, 961–975. doi:https://doi.org/10.1007/s11367-016-1075-z

Shell. (2021, July 2). *Shell starts up Europe's largest PEM green hydrogen electrolyser.* Retrieved from www.shell.com: https://www.shell.com/news-and-insights/newsroom/news-and-media-releases/2021/shell-starts-up-europes-largest-pem-green-hydrogen-electrolyser.html

Standards, I. (2020). *International Standards.* Retrieved from International Standards: https://iec.ch/publications/international-standards

Sumitomo. (2022). *Hokkaido Electric Power Networkv*. Retrieved from sumitomoelectric.com: https://sumitomoelectric.com/products/flow-batteries/case-studies/hokkaido-wind-integration

Viswanathan, v., Mongird, K., Franks, R., Li, X., & Sprenkle, V. (2022). 2022 Grid Energy Storage Technology Cost and Performance Assessment.

Yildiz, N., Hemida, H., & Baniotopoulos, C. (2024). Operation, Maintenance, and Decommissioning Cost in Life-Cycle Cost Analysis of Floating Wind Turbines. *Energies* (Article 6). doi:https://doi.org/10.3390/en17061332