i-STENTORE

innovative Energy Storage
TEchnologies TOwards increased
Renewables integration and
Efficient Operation

D2.1

SOTA ANALYSIS, BARRIERS, REGULATORY FRAMEWORK AND USE CASES’ DESCRIPTIONS

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Abstract	This deliverable explores the integration, barriers and regulatory landscape of energy storage technologies within the European power systems. Under the i-STENTORE project, funded by the European Union, this report was divided into three sections related with three tasks of the project: T2.1 Analysis of Energy Storage Technologies, T2.2 Conceptualizing Storage and Regulatory Assessment, and T2.4 Analysis of Energy Storage Deployment Barriers.
Keywords	Energy storage technologies state of the art, Hybrid ESS characteristics, Regulatory landscape, Deployment barriers

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TABLE OF ABBREVIATIONS AND ACRONYMS

aFRR	automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
BSP	Balance Service Providers
BTM	Behind the Meter
CAPEX	Capital Expenditure
DSO	Distribution System Operator
EBGL	Electricity Balancing Guideline
EC	European Commission
ENTSO-E	European association for the cooperation of transmission system operators
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FCR	Frequency containment reserve
FTM	Front the Meter
HESS	Hybrid Energy Storage Systems
IGCC	International Grid Control Cooperation
IPTO	Independent Power Transmission Operator
LCA	Life Cycle Analysis
LCS	Levelized Costs of Storage

LFC	Load – Frequency Control
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Restoration Reserve
OPEX	Operational Expenditure
PHES	Pumped Hydro Energy Storage
PICASSO	Platform for International Coordination of Automated Frequency Restoration and Stable System Operation
REN	Redes Energéticas Nacionais
RES	Renewable Energy Resources
RR	Replacement reserve
SLB	Second Life-Batteries
TERRE	Trans-European Restoration Reserves Exchange
TOU	Time of Use
TRL	Technology Readiness Level
TSO	transmission System Operator
UVAM	Virtual Mixed Aggregated Unit
VPP	Virtual Power Plant

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EXECUTIVE SUMMARY

This deliverable explores the integration, barriers and regulatory landscape of energy storage technologies within the European power systems. Under the i-STENTORE project, funded by the European Union, this report was divided into three sections related with three tasks of the project: T2.1 Analysis of Energy Storage Technologies, T2.2 Conceptualizing Storage and Regulatory Assessment, and T2.4 Analysis of Energy Storage Deployment Barriers.

Section 1: Analysis of Energy Storage Technologies (T2.1)

The first section, born from Task 2.1, offers an examination of the energy storage technologies' role within the European power systems. This analysis integrates technical and operational characteristics, recognizing the dynamic interplay between energy storage and renewable energy sources (RES). Engaging with a spectrum of energy storage systems, from pump-hydro to superconducting magnetic and thermal systems, the review addresses the potential that these technologies have to act as enablers for integrating variable RES and increase grid flexibility.

Section 2: Conceptualizing Storage and Regulatory Assessment (T2.2)

Task 2.2 lays the groundwork for energy storage integration considering existing regulatory frameworks. This section also presents comprehensive use cases, harmonizing end users' requirements and stakeholders' interactions in alignment with the IEC-62559 standard.

Section 3: Analysis of Energy Storage Deployment Barriers (T2.4)

The third section navigates through economic, regulatory, societal, and technological barriers. This analysis identifies critical constraints, offering potential solutions to overcome them. The exploration of societal perceptions, materials dependency, and regulatory gaps is used to shape a comprehensive understanding of the challenges and opportunities inherent to energy storage deployment.

Collective Impact and Vision

The technical analysis, regulatory assessment, and barrier identification made in this deliverable provides insightful information that can help to shape the energy landscape of the future. In harmony with the European Union's sustainability goals, the deliverable provides insights that empower the integration of renewable energy and energy storage systems.

1 ANALYSIS OF ENERGY STORAGE TECHNOLOGIES

In the era of renewable energy dominance, the importance of efficient and adaptable storage solutions has become increasingly evident. Recognizing this critical need, the i-STENTORE project is trying to foster the integration and hybridization of various storage technologies. With a strong focus on reliability, power quality, cost-efficient operation, and asset longevity, i-STENTORE aims to optimize the cooperation between innovative storage systems and integrated assets. In i-STENTORE, a comprehensive framework will be introduced, showcasing both stand-alone and hybrid storage solutions that highlight versatile applications of storage beyond its traditional role as an energy buffer. Instead, storage will be positioned as an active grid component capable of providing valuable services that contribute to grid resilience, stability, and efficient operation.

Task 2.1 of the i-STENTORE project focuses on a comprehensive analysis of the existing technical capacities concerning the utilization of energy storage technologies and their connection with renewables and other assets within the European power system. This analysis aims to grasp good practices from previous projects and address the challenges associated with integrating variable power sources, particularly renewable energy, into the existing power grids due to their stochastic characteristics. The task begins with an in-depth review of energy storage technologies currently deployed for power applications. This review encompasses a wide range of technologies, including pump-hydro, compressed-air, battery, flywheel, capacitor, supercapacitor, superconducting magnetic, and thermal systems. Special attention will be given to their unique characteristics, as these can serve as a basis for unlocking their promising potential in various applications. By harnessing these technologies, the adverse effects of intermittent renewable resources on networks can be mitigated, enabling higher utilization of renewable energy, and providing flexibility and ancillary services to manage future electricity supply and demand challenges.

1.1 RELATED PROJECTS

The SENSIBLE project (call LCE-08-2014) focuses on the integration of electro-chemical, electro-mechanical, and thermal storage technologies, along with micro-generation systems such as combined heat and power (CHP), heat pumps, and renewable energy sources like photovoltaics (PV). This ambitious endeavour aims to seamlessly integrate these technologies into power and energy networks, as well as homes and buildings, in order to unlock the benefits of storage integration. To showcase the potential of storage, three demonstrators were implemented in Portugal, the UK, and Germany. The city of Évora in Portugal served as a demonstrator for storage-enabled power flow, power quality control, and grid resilience in predominantly low-voltage power distribution networks. This demonstration addressed the challenges posed by weak and potentially unreliable networks, highlighting the role of storage in ensuring reliable and robust energy supply. Nottingham in the UK focused on storage-enabled energy management and the participation of buildings and communities in energy markets. With a grid assumed to be strong and offering minimal restrictions, this demonstration will explore how storage can optimize energy utilization, empower local communities, and enable participation in energy markets. Nuremberg in

Germany will concentrate on multi-modal energy storage in larger buildings, incorporating thermal storage, CHP systems, and various energy vectors such as electricity and gas. By examining different storage technologies and their integration into the energy infrastructure, this demonstration offered valuable insights into optimizing energy flows and utilization within buildings. An essential aspect of the SENSIBLE project revolves around connecting local storage capacities with energy markets to create sustainable business models for small-scale storage deployment, particularly in buildings and communities. Life cycle analyses and assessments of the socio-economic impact of integrating small-scale storage into building distribution networks will also be conducted, ensuring a holistic evaluation of the project's outcomes. Through the integration of diverse storage technologies into local energy grids, homes, and buildings, and by establishing connections to energy markets, the SENSIBLE project aims to significantly impact local energy flows and energy utilization. The envisioned outcomes range from increased self-sufficiency, improved power quality, and enhanced network stability to the development of sustainable business models for local energy generation and storage. By spearheading this transformative effort, the SENSIBLE project seeks to pave the way for a more sustainable and resilient energy future.

The development of Smart Energy Networks stands as a crucial priority in enabling the transition towards a more sustainable energy supply in Europe. Among the technologies showing great promise in improving the penetration of renewable energy sources (RES) and enhancing energy management in the European grid, lithium-ion (Li-ion) batteries have emerged as a frontrunner. With the goal of facilitating the deployment of safe stationary batteries with a significant energy content of over 1 MWh and cell sizes larger than 10 Ah, the STABALID project aims to address key challenges in this domain. The overarching objective of the project is to develop a new testing procedure for stationary batteries, ultimately establishing it as an international standard document for this particular energy system. The development of this safety testing procedure will be based on a thorough risk analysis and an extensive review of existing international standards, including those still in preparation, that are applicable to stationary batteries. The project will also incorporate ongoing research on Li-ion batteries and Electric Vehicle charging at both EU and national levels, drawing insights from initiatives such as HELIOS, MERGE, and SOL-ION. Ensuring safety throughout the entire lifecycle of the batteries is a critical aspect of the new standard that will be developed. To achieve this, the consortium behind the STABALID project will propose a comprehensive strategy and roadmap aimed at establishing a harmonized regulatory framework. This framework will facilitate the safe implementation, operation, and end-of-life management of large Li-ion batteries intended for grid applications. Notably, the project will collaborate closely with selected projects financed by METI and NEDO in Japan, fostering international cooperation and knowledge exchange.

The STALLION project takes a significant leap towards ensuring the safety of large stationary Lithium-Ion batteries throughout their entire life cycle, covering crucial stages such as commissioning, transport, installation, operation, maintenance, repair, and decommissioning. By offering a unique approach that addresses safety concerns at all levels of the system, ranging from material and cell to module, pack, and system, this project aims to develop and validate a comprehensive safety framework. Drawing on the expertise of partners actively involved at each level of the system and guidance from an advisory board consisting of experienced organizations, the project ensures a comprehensive understanding of cross-cutting safety issues. To establish the state of the art in relevant technological areas like materials, cell architecture, and detection methods, the project conducted a benchmark analysis of the market for large stationary battery systems. Based on this comprehensive assessment, mitigation measures were defined to address identified risks and bring the system within predefined safe boundaries. The outcomes of the project culminated in the development of a comprehensive and generic safety handbook for large grid-connected batteries. This handbook provides detailed guidance on safety measures derived from the project's findings and proposed standardization bodies through the involvement of standardization organizations within the Advisory Board. Furthermore, active distribution of the handbook to industry stakeholders will contribute to the standardization framework for large-scale Li-ion battery testing, ultimately facilitating a faster and safer deployment of Li-ion Batteries for grid applications.

Hydropower serves as the cornerstone of Europe's renewable electricity system, providing a reliable and clean source of energy. While Europe has established a strong hydropower market, there are still opportunities for this sector to flourish in other parts of the world. The EU-funded HYPOSO project aims to support the European hydropower industry while fostering sustainable development in selected target countries in Africa and Latin America, including Bolivia, Colombia, Ecuador, Cameroon, and Uganda. By combining a range of tools such as market analyses, exploration of untapped hydropower potential through GIS mapping, political and legislative frameworks, smart financing strategies, capacity building, and replicable business case studies, HYPOSO aims to achieve its objectives. The project will also facilitate collaboration between representatives of the European hydropower industry, their counterparts, and politicians from the target countries. Through these efforts, HYPOSO seeks to leverage the expertise of the European hydropower industry to support the transition to a more sustainable energy system in these regions, while addressing socio-economic, spatial, and environmental considerations. By identifying pilot projects, providing capacity building, and engaging in communication activities, HYPOSO aims to promote the European hydropower industry, create better investment conditions, and increase the share of renewable energy in the targeted countries. The project will also contribute to the development of policies, market support mechanisms, and financial frameworks at the local, national, and regional levels for hydropower facilities.

The development of new energy storage technologies is crucial for achieving balanced and flexible grids, addressing the intermittency of renewable energy sources, and overcoming seasonal energy storage challenges. In line with these goals, the EU-funded StoRIES project aims to foster an ecosystem of industry and research organizations in Europe, dedicated to the development of innovative and cost-effective energy storage technologies. The consortium comprises 32 beneficiaries from 17 countries, including members of the European Energy Research Alliance and the European Association for Storage of Energy. By providing access to cutting-edge research infrastructures and services, the project will accelerate the progress of knowledge and technology in the field of energy storage. One of the key technological objectives of StoRIES is to optimize hybrid energy systems, leveraging the strengths of different storage technologies. Aligned with the objectives of the European Green Deal, StoRIES recognizes that economic viability is a critical challenge for energy storage development. To address this, the project aims to create a European ecosystem that brings together industry and research organizations, facilitating the development of novel concepts and technologies. By leveraging the expertise of ESFRI facilities, technology institutes, universities, and industrial partners, StoRIES seeks to improve the economic performance of energy storage technologies. The project's objectives encompass various aspects, including enhancing materials for energy storage devices, optimizing hybrid energy systems, analyzing socio-technical and environmental impacts, and providing training and education on these topics. StoRIES aims to significantly enhance the technological foundation for energy storage applications. Additionally, the project aims to establish an ecosystem that promotes open science and sets new standards for energy technology through collaboration with international peer partners from the research and industry sectors. By advancing innovation and driving the adoption of more competitive and cost-effective energy storage solutions, StoRIES contributes to the European energy transition and the achievement of a sustainable and resilient energy system.

As technology seeks to revolutionize the energy storage landscape, the need for reliable, safe, and cost-effective batteries has become increasingly pressing. Moreover, reducing dependence on critical raw materials and establishing sustainable value chains throughout the battery lifecycle, from mining to recycling, is paramount. Embracing the opportunities presented by the digital era, the EU-funded BATTERY 2030+ project takes a multidisciplinary and cross-sectoral approach to charting the course for future European batteries. With a focus on strategic applications, the project brings together 17 leading partners from nine EU Member States, pooling their expertise and skills to drive innovation in battery technology. The objective of BATTERY 2030+ is to pave the way for a new generation of batteries that can deliver reliable and safe energy at low cost, while addressing concerns about critical raw materials and environmental sustainability. This necessitates a paradigm shift in the design and creation of batteries. By leveraging advanced techniques such as density functional theory calculations, machine learning, and artificial intelligence, the project aims to develop high-performance materials and structures from the atomic level up. Comprehensive data collected from characterization, synthesis, and testing will inform the design process, enabling batteries with high energy and power densities, rapid charging capabilities, and long-term durability, all while minimizing their environmental footprint.

Building upon the accomplishments of previous projects i-STENTORE embarks on a mission to explore and achieve new hybrid storage solutions that push the boundaries of energy storage technology. The project will delve into groundbreaking combinations such as integrating pumped hydro storage with Li-ion batteries and vanadium redox flow batteries, leveraging the potential of molten glass thermal storage in an end-fired hybrid regenerative furnace, and integrating a hydropower plant, wind farm, PV system, and Vanadium Redox Flow Battery with a dedicated storage facility. Additionally, i-STENTORE will explore the possibilities of integrating an electromechanical battery with a supercapacitor, as well as combining wind power, PV generation, an electrolyser, Li-ion battery, and hydrogen storage to create a comprehensive and sustainable energy ecosystem. Through these innovative hybrid solutions, i-STENTORE aims to unlock new levels of efficiency, reliability, and renewable energy utilization, contributing to the ongoing energy transition and shaping a more sustainable future.

1.2 ESS TECHNOLOGIES

Energy storage systems (ESS) refer to the technology used to capture, store, and distribute energy from various sources, such as solar, wind, and hydroelectric power. ESS plays a vital role in the integration of renewable energy sources into the power grid, as it enables the smooth distribution of energy contributing directly to mitigate its time variability. In addition, ESS can also be used to improve the reliability and stability of the power grid, and to provide backup power during power outages.

There are several types of ESS currently available, each with its own advantages and disadvantages. Some of the most common types include:

Chemical storage systems: These systems involve the conversion of energy into a chemical form, such as hydrogen, through electrolysis. The chemical product can then be stored and later converted back into electricity through a fuel cell or combustion. Chemical storage systems have a high energy density and are relatively inexpensive, but they have a limited life-cycle and require the use of expensive materials.

Thermal storage systems: These systems involve the storage of energy in the form of heat, which can be used to generate electricity through a steam turbine or a thermoelectric generator. Thermal storage systems have a relatively low energy density and require a large storage container, but they are relatively inexpensive and have a long-life cycle.

Pumped hydro storage systems: These systems involve the storage of energy in the form of water, which is pumped to a higher elevation when excess energy is available and then released through a turbine to generate electricity when needed. Pumped hydro storage systems have a high energy density and are relatively inexpensive, but they require a large storage container and a suitable location with a large difference in elevation.

Battery storage systems: These systems involve the storage of energy in the form of electricity, which can be stored in a battery and later released to the power grid when needed. Battery storage systems have a relatively high energy density, but they are relatively expensive and have a limited lifecycle.

Compressed air energy storage systems (CAESS): These systems involve the storage of energy in the form of compressed air, which can be released through a turbine to generate electricity when needed. CAESS have a relatively high energy density and are relatively inexpensive, but they require a large storage container and a suitable location with suitable underground caverns.

The selection of the most suitable ESS depends on the specific application and location. For example, battery storage systems are more suitable for small-scale applications, such as residential homes and small businesses, while large-scale applications, such as utilities and industrial facilities, may require more advanced and robust systems, such as pumped hydro storage or CAESS.

One of the main challenges facing the development of ESS is the cost. Currently, the cost of ESS is still relatively high compared to traditional power generation methods. However, as the demand for renewable energy increases and technology advances, the cost of ESS is expected to decrease. Additionally, the development of new and more advanced energy storage materials and technologies is also crucial for improving the performance and reducing the cost of ESS.

Another challenge facing ESS is the integration with the power grid. As the integration of renewable energy sources into the power grid increases, the need for effective ESS to manage the variability and uncertainty of these sources also increases. As such, there is a need for the development of advanced control and management systems to effectively integrate ESS with the power grid.

In conclusion, ESS plays a crucial role in the integration of renewable energy sources into the power grid and in the transition to a low-carbon economy. With continued research and development, ESS will become more efficient, cost-effective and can be a major contributor to the energy transition and sustainable future. ESS can provide the flexibility and reliability needed to support the integration of renewable energy sources into the power grid and can also help to improve the overall stability and reliability of the power grid.

In addition to their role in the power grid, ESS can also play a critical role in the transportation sector, particularly in the context of electric vehicles (EVs). ESS can be used to store energy generated by renewable sources, such as solar and wind, and can then be used to charge EVs, thus reducing the dependence on fossil fuels and mitigating the effects of climate change.

Furthermore, ESS can also be used in microgrids, which are small-scale power systems that can operate independently or in conjunction with the larger power grid. Microgrids are particularly useful in remote or off-grid areas and can provide a reliable and sustainable source of energy.

Overall, ESS is an important technology that can play a key role in the transition to a sustainable energy future. With continued research and development, ESS will become more efficient, cost-effective and can be a major contributor to the energy transition and sustainable future.

1.2.1 Gravitational ESS

Gravitational energy systems are an innovative type of energy storage system that stores potential energy by lifting heavy objects against the force of gravity. These systems operate on the principle of potential energy, where the energy is stored in an elevated object and then released when the object is lowered back to its original position.

Gravitational energy systems are an attractive energy storage solution for a number of reasons. First, they are a clean and sustainable technology that does not emit any greenhouse gases or pollutants. This makes them an environmentally friendly solution for storing and delivering energy.

Additionally, gravitational energy systems are highly efficient and have a long lifespan. The energy stored in the system can be released quickly and efficiently when needed, making it an ideal solution for applications with high power demands. Furthermore, the systems are made from durable materials, and require minimal maintenance over their lifespan, leading to lower operational costs.

One of the main advantages of gravitational energy systems is their flexibility. These systems can be scaled up or down depending on the energy demand, making them a versatile solution for a wide range of applications. Moreover, gravit/ational energy systems can be installed in a variety of locations, including remote areas where access to electricity is limited.

As the world transitions towards a more sustainable energy future, gravitational energy systems are becoming an increasingly important technology. With their efficiency, flexibility, and environmental benefits, these systems have the potential to revolutionize the way we store and deliver energy and play a key role in the transition to a clean energy future.

1.2.1.1 Advanced Rail ESS

Advanced rail energy storage system (ARESS) is an innovative technology that uses trains as a means of storing and delivering energy. This energy storage solution operates on the principle of kinetic energy, where a train is propelled uphill to store potential energy and then released downhill to generate electricity. The system uses electric motors to propel the train uphill, and then regenerative braking to generate electricity when the train rolls downhill.

One of the main benefits of advanced rail energy storage is its scalability. The system can be scaled up or down depending on the energy demand, making it a versatile solution for a wide range of applications. Furthermore, it is a clean and efficient technology that does not emit any greenhouse gases or pollutants, making it an environmentally friendly solution for energy storage [1].

FIGURE 1: ARESS TEHACHAPI PROJECT [2]

Another advantage of advanced rail energy storage is its low maintenance costs. The system requires minimal maintenance as it uses durable components and operates on a simple and efficient design. This results in lower operational costs and higher returns on investment.

The technology has been implemented in few real-world applications but it still lacks large scale production, this technology has a TRL of 6.

Advanced rail energy storage is an emerging technology that holds great promise for the future of energy storage. As renewable energy sources continue to grow, energy storage solutions like this one will become increasingly important in supporting the transition to a clean energy future. With its scalability, efficiency, and environmental benefits, advanced rail energy storage has the potential to revolutionize the way we store and deliver energy.

1.2.1.2 Pumped Hydro ESS

Pumped hydro energy storage (PHES) is a form of energy storage system (ESS) that uses the potential energy of water held at a higher elevation to store electrical energy. During times of low demand, excess electrical energy is used to pump water from a lower reservoir to an upper reservoir, thereby creating a potential energy difference. When electrical demand increases, water is released from the upper reservoir, flows downhill through turbines, and generates electricity. The energy generated by the turbines is then fed back into the electrical grid to meet demand.

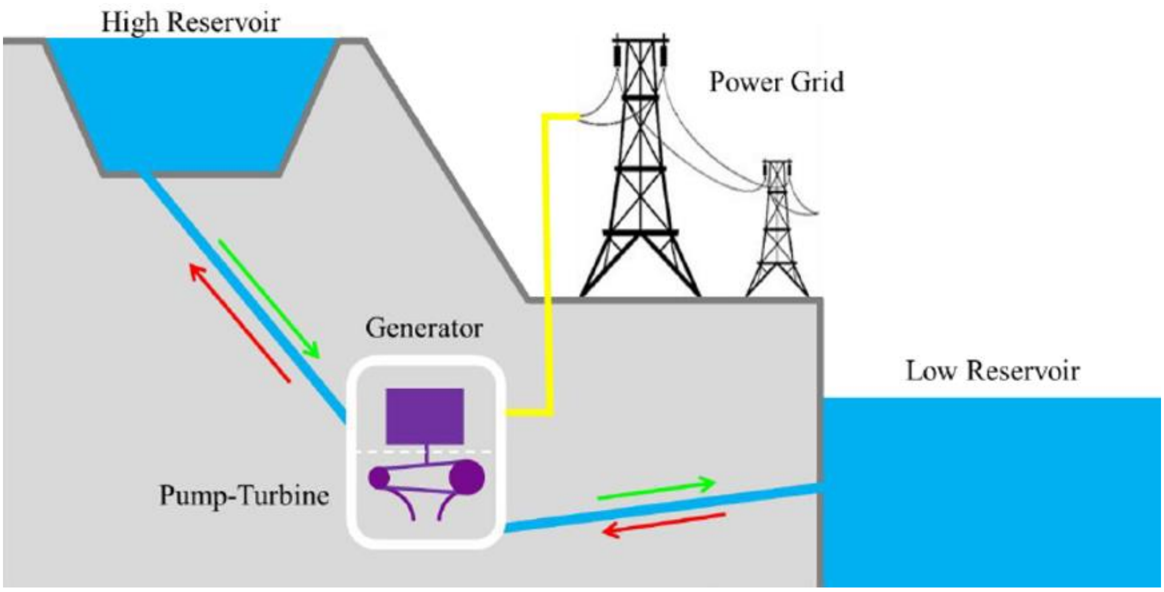

FIGURE 2: PUMPED HYDRO ENERGY PLANT, INCLUDING THE HYDRAULIC PUMP MODE AND TURBINE MODE [3].

In this way, PHES serves as a form of energy storage, allowing excess electrical energy to be stored and released as needed. PHES is a highly efficient form of energy storage, with conversion efficiencies ranging from 70% to 85%, making it one of the most effective methods of large-scale energy storage available today [4].

PHES systems require regular monitoring to ensure that they are operating within safe and efficient parameters. This includes monitoring water levels in the reservoirs, flow rates through the penstock, and electrical output from the generators. Control systems are typically used to manage the operation of the pumps and turbines, ensuring that they are operating optimally and efficiently.

PHES is a widely used type of storage system for many decades now, well established, and is considered to have the highest TRL, 9.

In conclusion, PHES is, in general, a critical component of a balanced energy system, as it can help to smooth out fluctuations in the electrical grid caused by intermittent renewable energy sources such as wind and solar. By providing a reliable and flexible source of stored energy, PHES can help to facilitate the integration of renewable energy into the grid, enabling the transition to a more sustainable and low-carbon energy system [5].

1.2.2 Mechanical ESS

Mechanical energy storage systems are an important component of the rapidly evolving energy landscape. Mechanical energy storage offers a promising avenue for storing energy in various forms and releasing it when needed, contributing to a more sustainable and resilient energy infrastructure.

Flywheel energy storage is a form of mechanical energy storage that relies on the rotational inertia of a spinning flywheel. Energy is stored by accelerating the flywheel to high speeds, and when energy is needed, the rotational energy of the flywheel is converted back into electricity. Flywheels have fast response times and can be used for short-term energy storage and high-power applications.

Mechanical energy storage systems have several advantages, including high energy density, long cycle life, and the ability to store energy for extended periods without significant degradation. They also offer the potential for large-scale deployment and cost-effectiveness compared to other energy storage technologies.

However, mechanical energy storage systems also face challenges. They often require substantial infrastructure, such as large reservoirs or underground storage facilities, and their geographical limitations may restrict widespread implementation. Additionally, efficiency losses during the energy conversion process and environmental considerations must be taken into account.

In conclusion, mechanical energy storage systems are a valuable component of the energy storage landscape, offering reliable, scalable, and sustainable solutions for storing and releasing energy. As research and development efforts continue, these systems hold the potential to play a significant role in enabling the widespread integration of renewable energy sources and ensuring a more resilient and efficient energy future.

1.2.2.1 Low-speed Flywheels

A low-speed flywheel is a type of flywheel that's designed to operate at lower rotational speeds typically in the range of 1,500 revolutions per minute (RPM), in contrast to high-speed flywheels, which can spin at speeds of up to 100,000 RPM or more. Low-speed flywheels are typically larger in diameter and have a greater moment of inertia than high-speed flywheels, which allows them to store more energy at lower speeds [6].

Low-speed flywheels have a variety of applications, including grid-scale energy storage such as in applications where energy storage and release is needed at a low frequency, as in microgrids, wind turbines, and solar power systems. They're especially useful in applications where high-power output is needed for short periods of time, like in electric vehicles or in the provision of backup power during a grid outage [7].

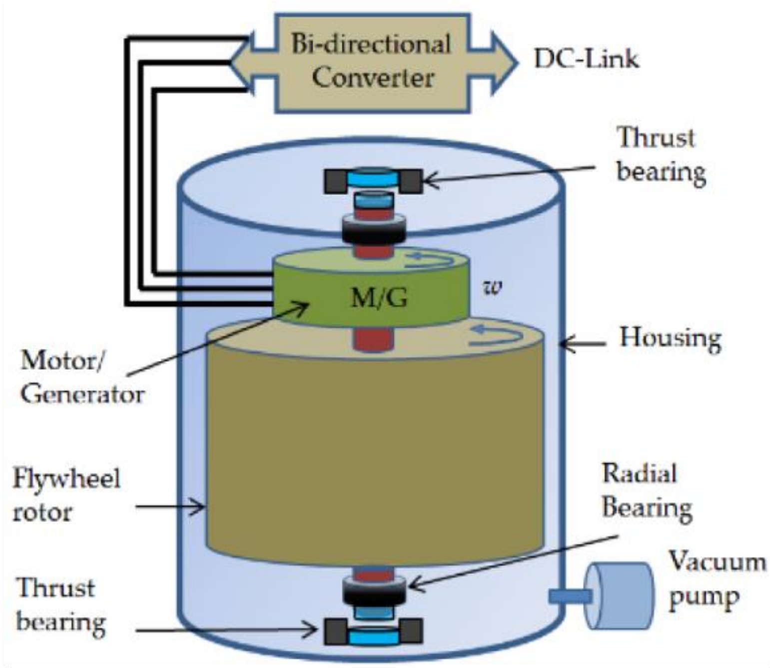

FIGURE 3: STRUCTURE AND COMPONENTS OF A FLYWHEEL. [7].

A low-speed flywheel typically consists of a large, heavy rotor that's mounted on bearings and enclosed in a vacuum chamber to minimize air resistance. The rotor is driven by an electric motor, which provides the input energy to spin the flywheel. As the rotor spins, it generates a significant amount of kinetic energy, which is stored in the flywheel as rotational energy. The amount of energy that can be stored depends on the mass and rotational speed of the flywheel, as well as the design of the bearings and other components [8].

When energy is needed, the rotational energy of the flywheel is converted back into electrical energy. This is done by connecting the flywheel to a generator, which converts the rotational energy into electrical energy that can be used to power a device or charge a battery. To regulate the speed and energy output of the flywheel, a control system is used. The control system typically includes sensors that monitor the speed and energy levels of the flywheel, as well as control algorithms that adjust the input and output of the motor and generator to maintain a constant speed and energy output.

Low-speed flywheels are mature storage systems with proven results in operational environment, thus making it a TRL 9 technology.

In conclusion, the advantages of low-speed flywheels is that they can be made from less expensive materials than high-speed flywheels, as they don't need to withstand the same high rotational speeds. This can make them more cost-effective for certain applications.

Additionally, low-speed flywheels can be designed to have very low friction, which can improve their efficiency and reduce energy losses [9].

1.2.3 Electrochemical ESS

Electrochemical energy storage systems play a crucial role in the world of energy by enabling the storage of electrical energy in the form of chemical energy, and then converting it back to electrical energy when needed. These systems can store energy generated from renewable sources such as solar and wind, and make it available on demand, even when the source is not producing power. The technology behind these systems has seen significant advances in recent years, and today, electrochemical energy storage systems are widely used in various applications, ranging from large-scale energy grid storage to portable electronic devices. In this chapter, we will delve into the fundamentals of electrochemical energy storage systems, understand their components, and explore different types of electrochemical energy storage systems, including batteries and supercapacitors. The challenges and future developments in the field of electrochemical energy storage will also be discussed.

1.2.3.1 Lead-Acid (Pb-A) Batteries

Lead-Acid (Pb-A) batteries are the oldest and most widely used form of rechargeable batteries in the world. These batteries have a long history of use in various applications, ranging from automotive to standby power and telecommunications. In this chapter, we will examine the basic principles of Lead-Acid batteries and their electrochemical behaviour. We will also discuss the different types of Lead-Acid batteries, including flooded, sealed, and valve-regulated Lead-Acid batteries, and compare their respective advantages and disadvantages.

Lead-Acid batteries operate based on the reaction between lead and lead dioxide electrodes in a sulfuric acid electrolyte. During charging, the sulfuric acid molecules are oxidized to form sulphate ions, leading to the production of electricity. During discharge, the sulphate ions are reduced to form sulfuric acid, producing electrical energy. The battery voltage is determined by the difference in the standard electrode potentials of the lead and lead dioxide electrodes [10].

Flooded Lead-Acid batteries are the most commonly used type of Lead-Acid batteries. They consist of lead electrodes immersed in a sulfuric acid electrolyte, which is free to circulate within the battery. Flooded Lead-Acid batteries require periodic maintenance and can be susceptible to leakage, making them less suitable for use in some applications.

Sealed Lead-Acid batteries, also known as maintenance-free batteries, are designed to prevent electrolyte leakage and eliminate the need for periodic maintenance. They are constructed with a sealed container that prevents the escape of electrolyte, making them ideal for use in portable electronic devices and backup power systems [11].

Valve-Regulated Lead-Acid batteries are a type of sealed Lead-Acid batteries that use a valve to regulate the pressure inside the battery. This type of battery is designed to minimize the risk of explosion and is often used in uninterruptible power supply (UPS) systems and telecom applications.

Lead-acid batteries are a well-established and widely used technology, having been in commercial use for many decades. As a result, lead-acid batteries are generally considered to have a high TRL, 9 (full-scale production).

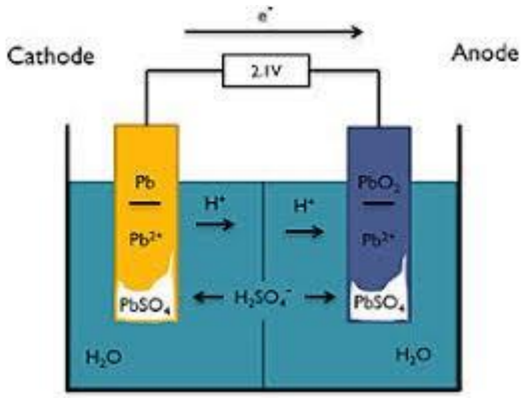

FIGURE 4: LEAD-ACID BATTERY SCHEME [12].

In conclusion, Lead-Acid batteries are a proven and reliable energy storage technology that have been widely used for over a century. Despite some limitations, they remain an important part of the energy storage landscape and will continue to play a crucial role in many applications, especially in backup power systems and automotive applications. Advances in Lead-Acid battery technology will continue to improve their performance and increase their efficiency, making them an even more attractive option for energy storage in the future.

1.2.3.2 Sodium Beta (Na-Beta) Batteries

Sodium-Beta (Na-β) batteries are a promising new type of energy storage technology that have gained significant attention in recent years due to their potential for high energy density and low cost. In this chapter, we will examine the basic principles of Sodium-Beta batteries and their electrochemical behaviour. We will also discuss the advantages and disadvantages of Sodium-Beta batteries and compare them to other energy storage technologies, including Lead-Acid and Lithium-Ion batteries.

Sodium-Beta batteries operate based on the reaction between sodium metal and beta-alumina electrodes in a molten sodium beta-alumina electrolyte. During charging, sodium ions are transported from the sodium electrode to the beta-alumina electrode, producing electrical energy. During discharge, the sodium ions are transported back to the sodium electrode, releasing electrical energy. The high energy density of Sodium-Beta batteries is due to the use of sodium metal as the anode and the high ionic conductivity of the beta-alumina electrolyte [13].

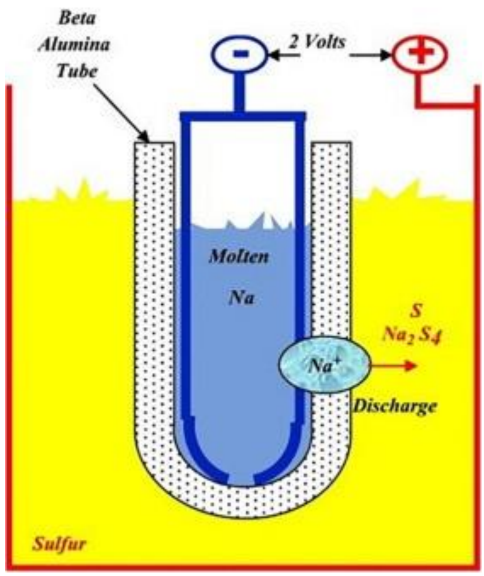

FIGURE 5: SODIUM-BETA BATTERY SCHEME [14].

One of the main advantages of Sodium-Beta batteries is their low cost, as sodium is abundant and inexpensive compared to other metals used in batteries, such as lithium. Sodium-Beta batteries also have a high energy density, making them suitable for large-scale energy storage applications. Additionally, Sodium-Beta batteries are safe and stable, with low risk of thermal runaway or fire.

However, there are also some limitations to Sodium-Beta batteries. One of the main challenges is the high operating temperature required for the battery, which can be difficult to achieve and maintain in some applications. Sodium-Beta batteries also have a lower power density compared to other energy storage technologies, making them less suitable for applications that require high power output [15].

The technology has progressed to the stage of a prototype system demonstrated in a relevant environment and it is considered to have a TRL of 5-7.

In conclusion, Sodium-Beta batteries are a promising new energy storage technology that offer high energy density and low cost. While they face some challenges, ongoing research, and development in the field of Sodium-Beta batteries will continue to improve their performance and increase their efficiency, making them a more attractive option for energy storage in the future.

1.2.3.3 Lithium (Li-ion) Batteries

Lithium-Ion (Li-Ion) batteries are a type of rechargeable energy storage technology that have gained widespread popularity in recent years due to their high energy density and long cycle life. In this chapter, we will examine the basic principles of Lithium-Ion batteries and their electrochemical behavior. We will also discuss the advantages and disadvantages of Lithium-Ion batteries and compare them to other energy storage technologies, including Lead-Acid and Sodium-Beta batteries.

Lithium-Ion batteries operate based on the transfer of lithium ions between a cathode and an anode during charging and discharge. The cathode typically contains a lithium-containing compound, such as lithium cobalt oxide (LiCoO2), while the anode is typically made of graphite. The electrolyte provides a medium for the transfer of lithium ions between the cathode and anode [16].

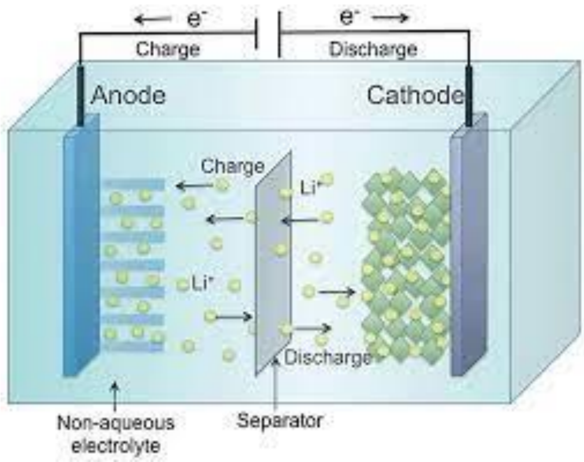

FIGURE 6: LITHIUM-ION BATTERY SCHEME [17].

One of the main advantages of Lithium-Ion batteries is their high energy density, which allows for compact and lightweight energy storage. Lithium-Ion batteries also have a long cycle life, typically several hundred cycles, and a high power density, making them suitable for applications that require high energy and power output. Additionally, Lithium-Ion batteries are safe and stable, with low risk of thermal runaway or fire.

However, there are also some disadvantages to Lithium-Ion batteries. One of the main challenges is the relatively high cost of lithium and the components used in Lithium-Ion batteries, making them less suitable for some large-scale energy storage applications. Lithium-Ion batteries also have a finite lifespan and can degrade over time, reducing their capacity and performance [18].

Lithium-ion (Li-ion) batteries are considered to be a mature technology with a high Technology Readiness Level (TRL). The technology has been successfully demonstrated in actual operating conditions and has been widely adopted in commercial applications thus have a TRL of 9.

In conclusion, Lithium-Ion batteries are a proven and reliable energy storage technology that have been widely adopted in a variety of applications, including consumer electronics and electric vehicles. Ongoing research and development in the field of Lithium-Ion batteries will continue to improve their performance and increase their efficiency, making them an even more attractive option for energy storage in the future.

1.2.3.4 Metal-air Batteries

Metal-Air batteries are a type of rechargeable energy storage technology that have gained significant attention in recent years due to their high energy density and low cost. In this chapter, we will examine the basic principles of Metal-Air batteries and their electrochemical behaviour. We will also discuss the advantages and disadvantages of Metal-Air batteries and compare them to other energy storage technologies, including Lead-Acid, Sodium-Beta, and Lithium-Ion batteries [19].

Metal-Air batteries operate based on the oxidation of a metal anode in the presence of air at the cathode, producing electrical energy. During discharge, the metal anode reacts with oxygen from the air to produce metal oxides and electrons, which flow through the external circuit to produce electrical energy. The cathode is simply air and the electrolyte provides a medium for the transfer of electrons between the anode and cathode.

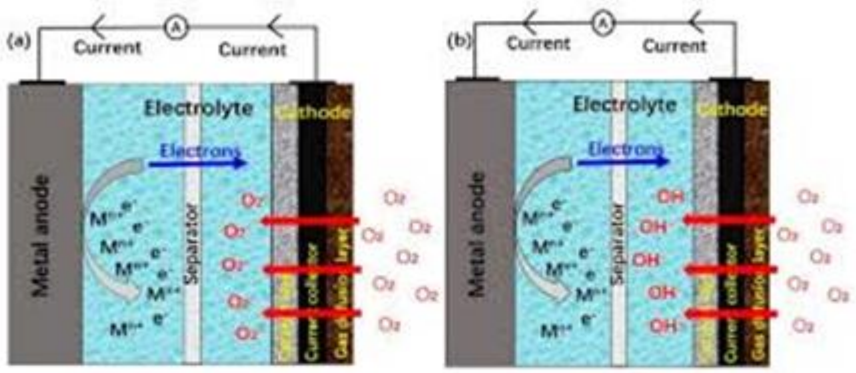

FIGURE 7: METAL-AIR BATTERY SCHEME [20].

One of the main advantages of Metal-Air batteries is their high energy density, as the cathode is simply air, making the battery relatively lightweight. Metal-Air batteries also have the potential for low cost, as the metal anodes can be made from inexpensive and abundant metals, such as zinc or aluminium.

However, there are also some limitations to Metal-Air batteries. One of the main challenges is the limited lifespan of the metal anode, as it gradually depletes during the discharge process. Metal-Air batteries also have a relatively low power density compared to other energy storage technologies, making them less suitable for applications that require high power output [21].

The technology has been demonstrated in a relevant environment or prototype system, TRL 5-7.

In conclusion, Metal-Air batteries are a promising new energy storage technology that offer high energy density and low cost. While they face some challenges, ongoing research and development in the field of Metal-Air batteries will continue to improve their performance and increase their efficiency, making them a more attractive option for energy storage in the future.

1.2.3.5 Nickel-based Batteries

Nickel-Based batteries are a type of rechargeable energy storage technology that have been widely used for decades in a variety of applications, including consumer electronics, electric vehicles, and backup power systems. In this chapter, we will examine the basic principles of Nickel-Based batteries and their electrochemical behaviour. We will also discuss the advantages and disadvantages of Nickel-Based batteries and compare them to other energy storage technologies, including Lead-Acid, Sodium-Beta, Lithium-Ion, and Metal-Air batteries.

Nickel-Based batteries operate based on the transfer of nickel ions between a cathode and anode during charging and discharge. The cathode typically contains nickel oxide (NiO) or a nickel-containing compound, while the anode is typically made of metal. The electrolyte provides a medium for the transfer of nickel ions between the cathode and anode [22].

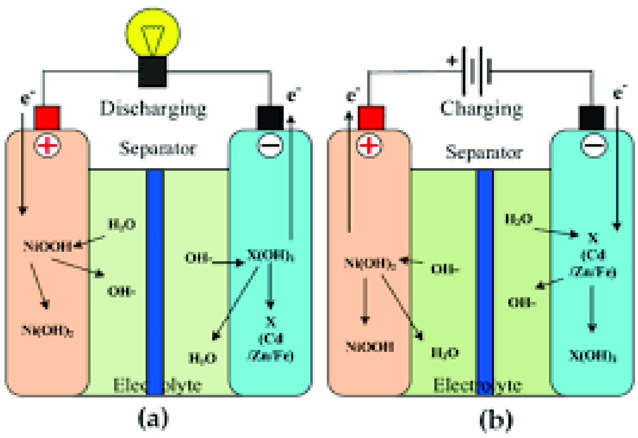

FIGURE 8: NICKEL BASED BATTERY SCHEME [23].

One of the main advantages of Nickel-Based batteries is their long cycle life, typically several hundred cycles, and good thermal stability, making them suitable for a variety of applications. Nickel-Based batteries also have a relatively low cost compared to other energy storage technologies, making them more accessible for some applications.

However, there are also some disadvantages to Nickel-Based batteries. One of the main challenges is their relatively low energy density compared to other energy storage technologies, making them less suitable for applications that require high energy output. Additionally, nickel can be toxic and hazardous to the environment, making it important to properly dispose of nickel-based batteries at the end of their lifecycle [24].

The technology has been proven to work in its final form and under expected operational conditions having a TRL of 8-9.

In conclusion, Nickel-Based batteries are a proven and reliable energy storage technology that have been widely used for many years. While they face some limitations, they continue to play an important role in the energy storage landscape, particularly in applications where long cycle life and low cost are a priority. Ongoing research and development in the field of Nickel-Based batteries will continue to improve their performance and make them an even more attractive option for energy storage in the future.

1.2.3.6 Flow Batteries

Flow batteries are a type of rechargeable energy storage technology that have gained significant attention in recent years due to their ability to store and release large amounts of energy. In this chapter, we will examine the basic principles of Flow batteries and their electrochemical behaviour. We will also discuss the advantages and disadvantages of Flow batteries and compare them to other energy storage technologies, including Lead-Acid, Sodium-Beta, Lithium-Ion, Metal-Air, and Nickel-Based batteries.

Flow batteries operate by storing energy in two tanks that contain the positive and negative electrodes, separated by a membrane. During charging, the positive and negative electrode materials are stored in the tanks, and during discharge, the electrode materials are pumped through the cell where they react to produce electrical energy. The use of tanks to store the electrode materials provides Flow batteries with the ability to store and release large amounts of energy, making them suitable for a variety of energy storage applications [25].

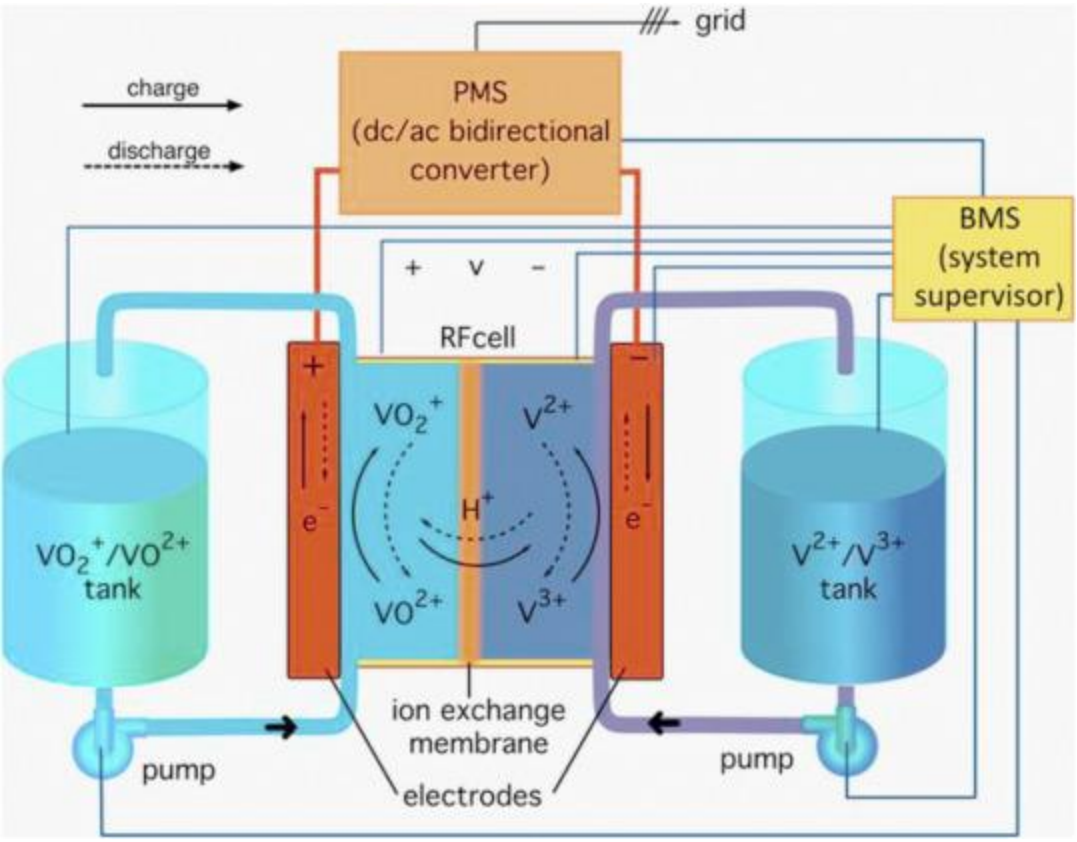

FIGURE 9: FLOW BATTERY SCHEME [26]

One of the main advantages of Flow batteries is their scalability, as the amount of energy that can be stored can be increased by increasing the size of the tanks. Flow batteries also have a long cycle life, typically several thousand cycles, making them suitable for a variety of applications.

However, there are also some disadvantages to Flow batteries. One of the main challenges is their relatively low energy density compared to other energy storage technologies, making them less suitable for applications that require high energy output. Flow batteries also require the use of pumps and other mechanical components, which can add to their cost and decrease their efficiency [27].

VRFBs have been successfully demonstrated in a real-world operational environment, showcasing their functionality and potential benefits. This includes testing the batteries in practical applications, such as grid-scale energy storage projects or renewable energy integration scenarios. VRFB are considered to have a TRL of 7-8.

In conclusion, Flow batteries are a promising new energy storage technology that offers scalability and long cycle life. While they face some challenges, ongoing research and development in the field of Flow batteries will continue to improve their performance and make them a more attractive option for energy storage in the future. As renewable energy sources, such as wind and solar, continue to grow, the demand for large-scale energy storage solutions will likely increase, making Flow batteries a potential solution for meeting this demand.

1.2.3.7 Final remarks

In conclusion, the advancement of electrochemical energy storage systems has been nothing short of remarkable, playing a vital role in a wide range of applications from consumer electronics, electric vehicles, to backup power systems. Throughout this chapter, we delved into the intricacies of various battery technologies, including Lead-Acid, Sodium-Beta, Lithium-Ion, Metal-Air, Nickel-Based, and Flow batteries, each with its unique characteristics and strengths.

Lead-Acid batteries, with a long-standing history of use, offer reliability, yet fall short in terms of energy density. Sodium-Beta batteries possess high energy density, but are faced with challenges related to safety and cost. Lithium-Ion batteries, while highly efficient, boast a relatively high cost. Metal-Air batteries offer exceptional energy density, but their cycle life remains limited. Nickel-Based batteries, while cost-effective, exhibit low energy density. And, Flow batteries offer scalability and longevity, yet are limited in terms of energy density.

As renewable energy sources continue to grow, the need for large-scale energy storage solutions will only escalate, fuelling ongoing research and development in the field. In this rapidly evolving landscape, it will be imperative for new technologies to strike a balance between cost, safety, energy density, cycle life, and scalability to truly make a significant impact.

In essence, the future of electrochemical energy storage systems is poised for growth and innovation, with the potential to revolutionize the energy landscape for years to come. As scientists and engineers continue to push the boundaries, we can look forward to new and improved solutions for storing and releasing energy, fulfilling the ever-increasing demand of our energy-intensive world. The Table 1 summarizes the main characteristics of battery technology.

TABLE 1: BATTERY TECHNOLOGY OVERVIEW

Battery technology	Lead Acid	Na-Beta	Li-ion	Metal – Air	NiCd	Flow
Energy Density (Wh/L)	60-75	200-400	250-693	300-500(*)	50-150	10-50
Round-trip Efficiency (%)	70-90	75-90	85-95	50-65	60-90	60-75
Cost($/kWh)	64-164	40-77	115-151	409	300-400	275-450
Life time (years)	5-15	10-15	5-15	0.17-30	5-20	15-30
Power Density (W/Kg)	150	110-150	260-270	764	50-75	10-100
Daily self-discharge (%)	0.1-0.4	0.05-20	0.03	~0	0.1-0.2	~0
TRL	9	5-7	9	5-7	8-9	7-8

1.2.4 Thermal ESS

The technological classification of Thermal Energy Storage Systems (TES Systems or TESS) comprises three main categories [28]; Sensible Heat Storage, Latent Heat Storage and Thermochemical Heat Storage.

1.2.4.1 Thermomechanical ESS

Sensible Heat Storage (HS) is the most common and widely used ESS, mostly due to its simplicity and low cost. In this technological approach the energy is stored in a storage medium which can either be liquid or solid, with its temperature increasing, without changing its phase. The process of storing is reversible, so heat can be extracted from the medium, lowering its temperature.

Liquid Sensible HS and Stratification: The most common liquid used for thermal heat exchange in Liquid Sensible HS is water due to its high availability, low cost, ease of handling, high heat capacity and good thermal conductivity. Other storage materials include organic fluids, molten salts or oils. The design and the efficiency of water-based systems depends on tank size, insulation, stratification [29] (i.e., the formation of layers of the fluid in different temperatures while inside the medium) and heat-exchanger performance. In some cases, stratification is desirable as it can allow for efficient charging and discharging of the thermal energy.

Solid-media Sensible HS: Solid-media TESS store thermal energy usually in rocks, sand or concrete. They are favoured for employment for their high-temperature storage properties, without undergoing a phase change. Solid-media TESS are further categorized into two categories; Packet Bed and Fluidized Bed systems [30]. The storage medium in the Packed bed systems is arranged so that the heat transfer fluid (like air, steam, oil) circulates through a fixed bed structure (a medium made by rocks or ceramic) to either transfer heat to or from the medium. Such systems are suitable for high-temperature applications, like concentrated solar power (CSP) plants, industrial waste heat recovery and building energy management (BEM). Fluidized bed systems differ from the Packed bed type as the solid storage medium is not fixed but in particles (like sand or ceramic), which are 'fluidized' by the flow of the heat transfer fluid (e.g., oil, air). The particle-motion of the storage medium offers better heat-transfer rates, lower pressure drops, better mixing and temperature uniformity, when compared to packed-bed systems. However, they present higher complexity in design, operation and maintenance when compared to packed-bed systems as they need to maintain fluidization and particle motion control.

Latent HS: Conversely to Sensible HS, the Latent HS employs phase change materials (PCMs) for storing and releasing thermal energy, by exploiting the phase-change transition phenomenon (typically between the solid and liquid states of the materials).

PCMs can absorb or release large amounts of heat at nearly constant temperature, which is a property that enables Latent HS to achieve high energy storage density and temperature stability. PCMs [31], [32] may be organic materials (e.g., paraffins, fatty acids), inorganic materials (e.g., salt hydrates, metallic alloys) and eutectic mixtures. The choice of the proper material depends on the desired operating temperature, the thermal conductivity, and the cycling stability. PCMs are usually encapsulated [33] or embedded in building materials forming composite structures.

Eutectic[34] systems are created by mixing two or more components so that the compound will present a lower melting point that the individual constituents. Similar to PCMs, when a eutectic mixture undergoes a phase transition it exchanges energy (absorbs or releases heat at a constant temperature). In comparison to PCMs, eutectic systems offer precise melting points, reduced phase separation and better cycling stability. Common applications of PCMs and eutectics include BEM (space heating, cooling, hot water supply), renewable energy integration (solar thermal) and industrial waste heat storage.

The Technology Readiness Level (TRL) of the liquid sensible heat storage technologies varies greatly depending on the technological application. For water-based storages (low and medium temperatures) the TRL is 9 given that these technologies are very mature. The oil-based storages (higher temperatures) generally present a TRL of 7 to 9, depending on the application. For the case of high-temperatures, like the CSPs, the TRL for plants using molten salts is around 8 to 9, however there are cases where TRL is lower (around 4 to 6 since) for technologies that are in the stages of component and system validation (usually in lab environments). Many solid-media HS technologies that are used in low and medium temperature applications (like the ones using concrete or ceramic materials for buildings) have a high TRL (from 7 to 9) since these have already been demonstrated in operational environments or deployed in practical applications. As to the latent HS, the PCMs used in building materials present a TRL from 7 to 9. The encapsulated PCMs (small capsules with a PCM), and the PCMs used in large-scale systems (often using salt hydrates or paraffin wax), pose a TRL around 5 to 7. As to the technologies of eutectic systems, the ones that are based on salt mixtures and organic compounds present a TRL of 6 to 7 and in some cases (eutectic salts used in advanced solar thermal plants) present a TRL of 8.

1.2.4.2 Thermochemical ESS

Thermochemical HS (TCHS) systems exchange thermal energy through reversible endo- and exo-thermic chemical reactions. Unlike the other two categories, TCHS can store energy for long periods without significant losses since storing is achieved by the formation or deformation of chemical bonds rather than relying on temperature differences where constraining or driving the thermal flow can be more challenging. Also, TCHS offer high density storage and the potential for high-operating temperatures. The two main types of TCHS systems are sorption-based and chemical reaction-based. The Sorption-based [35] TCHS systems involve the reversible absorption or adsorption of a fluid (usually water vapor or ammonia) into or onto a solid sorbent material (usually silica gel, zeolites or metal-organic frameworks). The heat exchange is based on endo- or exo-thermic reactions. The endothermic reactions occur when the desorption of the fluid from the sorbent receives heat; conversely for the exothermic reactions. The Chemical Reaction-based TCHS [36] systems exchange thermal energy through reversible chemical reactions, like metal-hydride or metal-oxide reactions. When charging with heat, an endothermic reaction takes place which requires heat input to dissociate the reactants. The dissociation products are stored separately so that the inverse reaction can take place when the reactants are recombined.

Storage Medium Selection: The storage medium to be selected depends on various factors. For the Sensible and Latent HS, it mostly depends on the desired temperature range, the thermal properties, the material compatibility, and system requirements. For the Sorption-based TCHS the sorbent material and working fluid depends mostly on the desired operating temperature, the energy storage density and the cycling stability, while for the Chemical Reaction-based TCHS it also depends on the reaction kinetics.

Applications - Challenges: Sensible HS with molten salts is widely used in CSP [37] plants due to its high operating temperature and thermal stability. Latent HS using PCMs and TCHS are also investigated in CSP applications as they offer higher energy storage density and the potential for higher operating temperatures [38]. Similarly, recent research focuses on improving solar water HS by the incorporation of Latent HS systems and PCMs or TCHS to enhance storage density and reduce heat losses [39].

In relation with the challenges, although Sensible HS present lower capital costs when compared to Latent HS, their lower energy storage density and potential heat losses may impact their overall cost-effectiveness. On the other hand, Latent HS using PCMs have higher material costs and more complex encapsulation techniques which may lead to cost-effective solutions when compared to Sensible HS. Additionally, TCHS can offer long-term and high-density storage with minimal heat losses but require specialized materials, R&D investments, and more complex designs.

Advanced Materials and Technologies: A promising innovation in Latent HS, demonstrated by several studies, is the nano-enhanced PCMs (NePCMs) which incorporate nanoparticles that multiply their benefits [40]. Typical applications include building envelopes and HVAC systems [41]. The research on Metal-organic frameworks (MOFs) [42], which are attractive candidates for TCHS, examines the performance of porous materials with high surface area, tuneable pore size and adjustable chemical functionality, in a pursuit towards the creation of materials with tailored properties [43].

The TCHS technologies are typically around a TRL of 4 to 6, since these are still in the development and testing phase with ongoing research that focuses on issues like the reaction kinetics, system integration and cost. The special cases of NePCMs have been lab validated (TRL 4) and parts of the technology has been tested in a relevant environment (TRL 5). The TRL of MOFs is around TRL 3 to 4.

Hybrid TESS combine the advantages of two or more storage technologies (such as Sensible HS and Latent HS or Latent HS and TCHS) to optimize performance and efficiency across various applications, by leveraging the advantages and mitigating the limitations of each. By addressing different time-scales of energy storage, hybrid TESS can improve the overall energy management from grid-level to BEM applications. Combining technologies that excel in different energy storage time scales and rates can create a system adaptable to varying energy demands and supply patterns throughout the year. An example of combined technologies is the utilization of PCM on a building integrated photovoltaic (BIPV) with thermal control [44]. Another example is a hybrid TESS incorporating the integration of PCMs into a Sensible HS tank, to enhance overall performance while maintaining the low cost and simplicity [45].

Combined cooling, heat and power (CCHP) [46] storage systems integrate TES with other forms of energy storage such as electrical of mechanical storage. By coupling TESS with other technologies these systems can improve the overall flexibility of a grid and a BEM system [47]. More specifically, integrated solar CHP (ISCHP) systems combine PV panels with TES and potentially other forms of storage, like batteries [48].

Finally, solar-assisted heating and cooling (SAHC) systems can store excess solar heat during periods of high solar radiation and release it during periods of low solar radiation or night-time ensuring a stable supply of energy for both types of applications [49].

The Hybrid TESS technologies present a TRL ranging from 5 to 7 as some have undergone validation in relevant environments (TRL 5), some demonstrated proper system/subsystem performance in relevant environments (TRL 6) and some demonstrated proper system prototype operation in operational environments (TRL 7). The CCHPs are employed in various sectors including industrial, commercial and residential applications, achieving a TRL of 8 to 9. Similarly, SAHC systems present a TRL of 9 since these technologies have been commercially available for some time, especially in countries with favourable conditions for solar energy accumulation. The main challenges in this technology relates to the initial cost, the availability of space for the collectors, and the seasonal mismatch between solar availability and heating/colling demand.

1.2.5 Electrical ESS

This chapter introduces two distinct classes of energy storage systems that rely on the storage of energy in the form of electric or magnetic fields. The first type of ESS in this category involves the generation of an electric field through the use of current, which then stores the energy. A commonly used device in this class is the capacitor, which charges its plates to create an electric field that stores electric energy and releases the energy when the capacitor is discharged. A more advanced device that offers higher energy and power density is the supercapacitor.

The second type of ESS in this category utilizes inductors, which rely on the dual principles of generating a magnetic field when an electric current flows through coils of wire. To prevent resistive losses in the coil, superconducting materials are required. Once the energy is stored in the magnetic field, it can be extracted as electricity from the advanced coil.

In the following, the above-mentioned ESSs will be described and their main features will be outlined.

1.2.5.1 Supercapacitor ESS

Capacitors are used to store electrical energy directly in electrostatic charge form. It consists of two metal plates separated by an air gap and when a voltage is applied to the terminal, the plates become statically charged. When the voltage is removed, the static charge will remain until a short circuit is applied between the plates.

The common capacitors have a capacitance smaller than 1 Farad in electrical and electronic applications.

A particular capacitor is used for ESS to provide a high capacitance. These devices are known as either Supercapacitors or Ultracapacitors or, more technically, electric double-layer capacitors (EDLC). The latter features an energy density hundreds of times greater than the conventional capacitor.

It has electrodes that act as the plates of the device, and these are immersed in an electrolyte that contains ions that can move between the plates. A semipermeable membrane in the electrolyte solution separates the plates to ensure any contact and create a short circuit. When a charge is applied to the capacitor, it causes the usual charge build-up. In this case, the charge on each plate is neutralized by an opposing layer of charged ions, called a Helmholtz layer, from the electrolyte. This creates a double charge layer at each plate, effectively leading to two capacitive charged layers, which massively increases the amount of charge that the unit can hold.

Figure 10 shows the charging behaviour in EDLC in different cases.

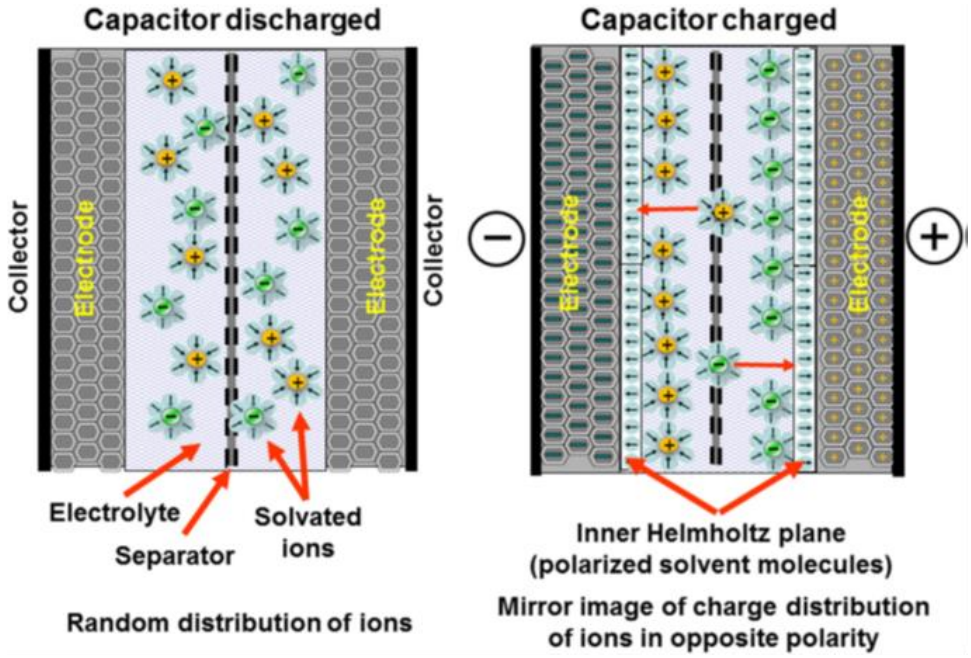

FIGURE 10: DIAGRAM OF A SYMMETRICAL ELECTROCHEMICAL CAPACITOR AT DISCHARGED AND CHARGED STATES [50].

To provide additional storage capacities, the electrodes are made by applying a porous coating, usually in carbon, to a metal electrode plate. The amount of charge depends on the surface area of the electrode since this is where the charge accumulates, so this is made larger as possible. The common electrolyte used in EDLC is a solvent with a dissolved material that dissociates into positively charged ions and negatively charged ions.

Figure 11 reports the structural difference between conventional capacitors and supercapacitors.

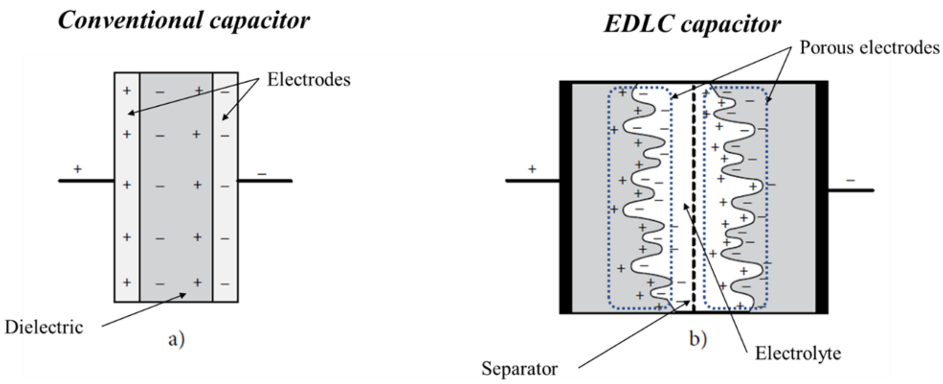

FIGURE 11: PRINCIPLE AND STRUCTURE OF CONVENTIONAL AND EDLC CAPACITORS [51].

Supercapacitors can be cycled tens of thousands of times and can normally discharge their energy very rapidly without degradation, thus the advantages are high power density, quick power delivery, high efficiency, and long-life operative time against batteries.

However, they are limited to a relatively small absolute energy storage capacity if compared with electrochemical ESSs, for instance, 10% of the energy density of Li-ion batteries.
This technology is used in a wide area of applications. The ideal unlimited lifetime and the fast response time are useful for railway and automotive applications for absorbing power spikes from braking energy recovery systems; for optimal efficiency and fast reaction. Additionally, this technology can be used as an ESS system (or HESS) for smart grid solutions to integrating renewable energy sources.
However, their small absolute storage capacities limit their use in many sectors but hybrid technology (such as lithium-ion capacitor (LiC)) and hybrid systems (shown above) reduce the disadvantages and offer the keys to investing in this solution.

Supercapacitors are available and in use for commercial and grid applications having TRL 9.

1.2.5.2 Superconducting Magnetic ESS

Superconducting magnetic energy storage (SMES) is a technologically advanced solution that stores energy in a magnetic field form. In the 1970s, the first studies on SMES appeared and then it's been a topic of interest for many scientists in the energy sectors.
The operating principle of this ESS is based on generating a magnetic field with a DC current from the source and keeping it constantly active if there is no demand for energy. The … shows the equivalent circuit of the ESS where the S_1 is closed and S_2 is opened when the energy is transferred; once the energy has been transferred by the power supply, switch S_1 is opened and switch S_2 is closed. The energy stored in the magnetic field is converted to heat by the current linked with it in the resistance R. The energy storage is therefore only of a very short duration.

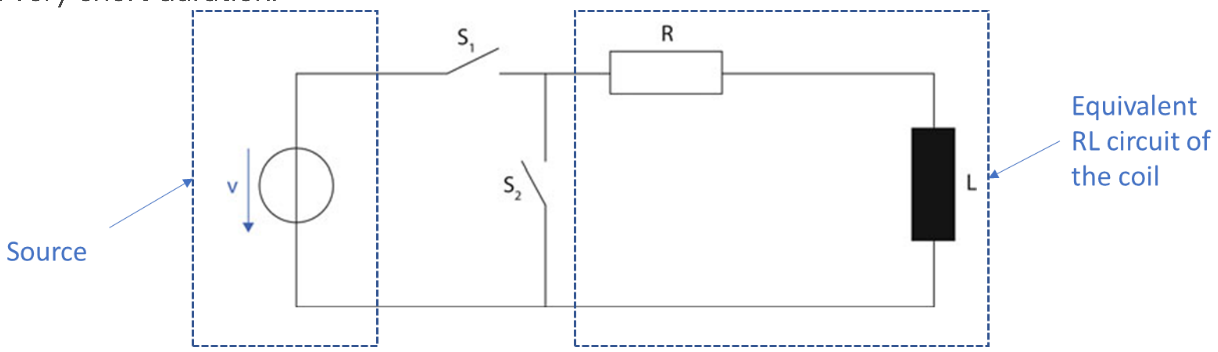

FIGURE 12: RL CIRCUIT REPRESENTED A SIMPLIFIED EQUIVALENT CIRCUIT FOR THE COIL WITH TWO SWITCHES [52].

The magnetized coil is made of superconductor material to guarantee no resistive energy losses during energy conservation.
A SMES design depends on two relevant factors:
Size and geometry of the coil;
Characteristics of the coil material.
The size of the coil is proportional to the amount of stored energy, and the main geometry topologies are solenoid and toroid forms. The solenoid shape is the most popular due to the considerable reduction in the number of conductors and lower structure cost.

The key to this ESS is superconductor material, which acquires the desired properties below the "transition temperature" [53] are two types of superconductive material:

- Low-temperature superconductor magnet (LTS);
- High-Temperature superconductor magnet (HTS).

The main differences are the value of the critical temperature (For LT superconductor T_{cr}=10°K, for HT superconductor T_{cr}=98°K), the efficiency of the energy systems with HTS tends to be less effective to the LTS but the LTS material must be cooled cryogenically to become superconducting.
The most widely and cheapest LT superconducting material is Niobium-Titanium and liquid helium is usually used to cool the coil. Ceramic materials can be used as HT superconducting materials with relatively high temperatures, but they are difficult to work on.
Next figure shows a schematic diagram of the SMES system for grid distribution.
The coil could be placed into a container for easy transport and installation. The SMES is interfaced with a power conditioning system for grid distribution application and a robust cooling system refrigerates the coil for temperatures below the critical temperature value to achieve superconductive properties.

SMESs are considered to have TRL 7.

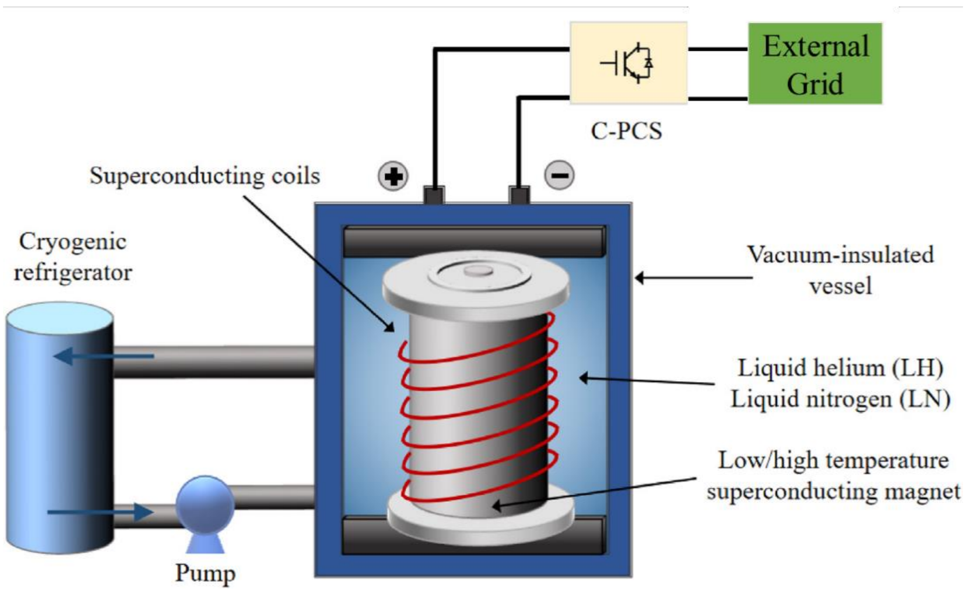

FIGURE 13: A SCHEMATIC DIAGRAM OF A SMES SYSTEM FOR GRID DISTRIBUTION [54].

In conclusion, SMES has high efficiency of energy transfer conversion (greater than 95%), a fast response time, and a long operative lifetime (more than 30 years). The disadvantages are a relatively lower energy density and the high capital cost of the entire system.
This technology is applied for load levelling and high-quality power when required such as UPS (Uninterruptible Power Supplies) and FACTS (Flexible AC Transmission System) applications.

The future of SMES may depend on the development of cheaper and usable higher-temperature superconductors with better properties. The goal would be to discover superconducting materials at ambient temperatures.

1.2.5.3 Final remarks

Table 2 and Table 3Table 3 contain some technical and economic features of the presented ESS and commercial ESS solution.

TABLE 2 - COMPARATIVE TABLE I [55]

Technology	Power rating	Discharge time	Discharge losses per day	Cycling capacity	Lifetime
	[MW]		[%]		[years]
Li-ion	0-0.1	Min-Hours	0.1-0.3	1000-10,000	5-15
Ni-Cd	0-40	Sec-Hours	0.2-0.6	2000-2500	10-20
SCES	0-0.3	Millisec – 60 min	20-40	100,000	20+
SMES	0.1-10	Millisec – 8 sec	10-15	100,000	20+

TABLE 3 - COMPARATIVE TABLE II [55]

Technology	Energy density	Power density	Efficiency	Cost	
	[Wh/kg]	[W/kg]	[%]	[$/kWh]	[$/kW]
Li-ion	75-200	150-315	85-89	600-2500	1200-4000
Ni-Cd	50-75	150-300	72	800-1500	500-1500
SCES	2.5-15	5000-10000	>95	300-2000	100-300
SMES	0.5-5	500-2000	>95	1000-10,000	200-300

The diagram in FIGURE 14 is used for comparing the energy density and power density of various ESS devices.

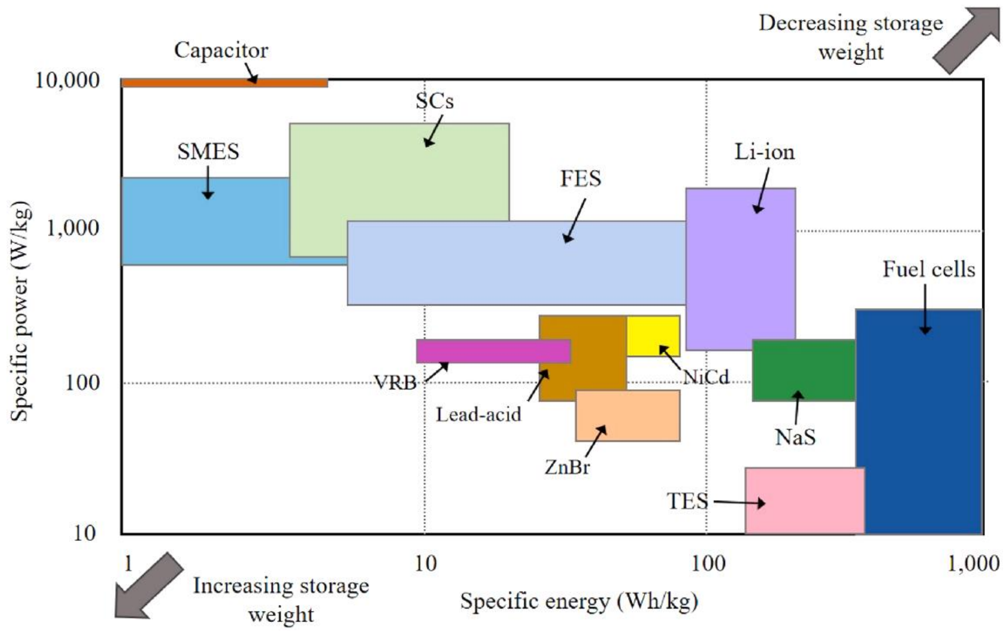

FIGURE 14 - RAGONE DIAGRAM SHOWING THE ENERGY DENSITY VERSUS POWER DENSITY OF DIFFERENT ESS TECHNOLOGIES [54].

1.3 CHEMICAL ESS

Chemical energy storage systems (CESS) are characterized by storing energy in the form of chemical fuels. Despite the broad range of fuels used for storing energy, such as coal, oil, or natural gas, most of those are non-renewable and produce pollutants that highly contribute to environmental degradation and climate change. Current trends look to overcome those obvious disadvantages by focusing on the research and development of reversible green CESS technology based also on fuels such as green hydrogen [56], [57].

In this chapter the concept of the Compressed Air Energy Storage is analyzed while a classification and a comparison among different technologies of CAES systems takes place. The general concept behind energy storage system technologies is to store the excess energy, produced by conventional or renewable energy sources and use it when required, in order to maintain the stability and flexibility of the power grid. The same applies to CAES system, whose operation will be described below. However, according to the literature, building an underground reservoir or cavern to store the compressed air and all the necessary equipment for a CAES system can be expensive, making it difficult to compete with other energy storage technologies [56][57].

The CESS has great advantages compared with other forms of energy storage mainly because of the green fuel's energy densities and energy end-use flexibility offered by the type of energy produced (*e.g.* electrical, kinetic, or thermal), *i.e.* power-to-X (P2X). Some of the different end-use configurations can be described as [58]:

- Power-to-power (P2P): green fuels used to produce electricity.
- power-to-gas (P2G): green hydrogen-enriched natural gas.

- power-to-mobility (P2M): green fuels to be used on thermal engines or electric motors with fuel cells.
- power-to-industry (P2I): green fuels to produce thermal energy of material compounds required by the industry.

To reduce the scope of this document and consider the project alignment, the following analysis is focused on green CESS following a power-to-power (P2P) approach to highlight the CESS potential to operate as a battery. Figure 1 illustrates the green hydrogen value chain, where the fuel cell enables the conversion of the energy stored in the hydrogen into electricity and reversibility is attained with the electrolyser that makes use of electricity to produce hydrogen.

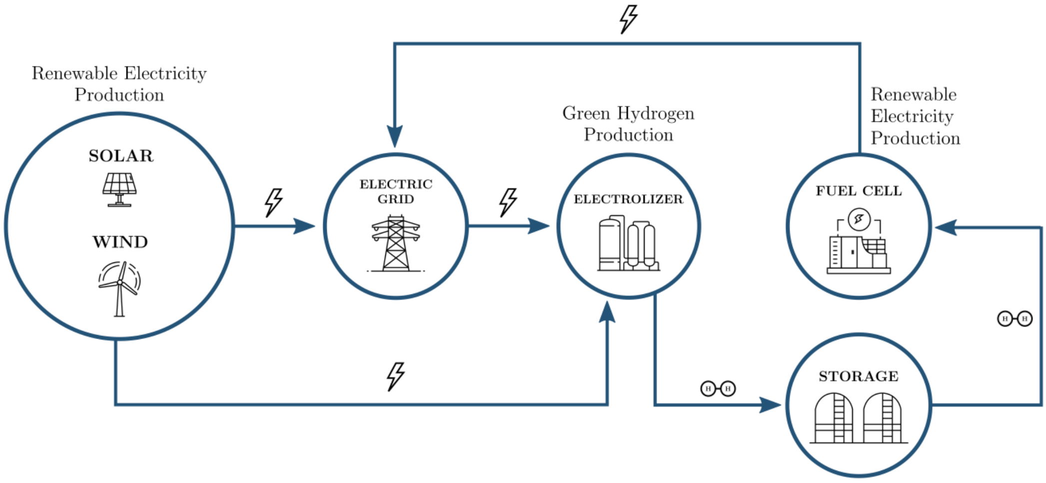

FIGURE 15: P2P GREEN HYDROGEN VALUE CHAIN [58].

1.3.1 Electrolysers

The electrolyser is a device that uses electricity for the separation of water molecules into hydrogen and oxygen (also known as water-splitting) when a DC voltage is applied to two electrodes, where at least one is in contact with water. The resulting chemical reaction (1) illustrates the water-splitting process.

$$H_2O_{(l)} \xrightarrow{electricity+heat} H_{2\,(g)} + 0.5\ O_{2\,(g)} \qquad (1)$$

There are three main technologies for water electrolysis: alkaline water electrolysis (AEL), proton-exchange membrane electrolysis (PEMEL) and solid oxide electrolysis (SOEL). Information regarding the basic principle of work of each technology is described in [58], [59] as illustrated in Figure 16.

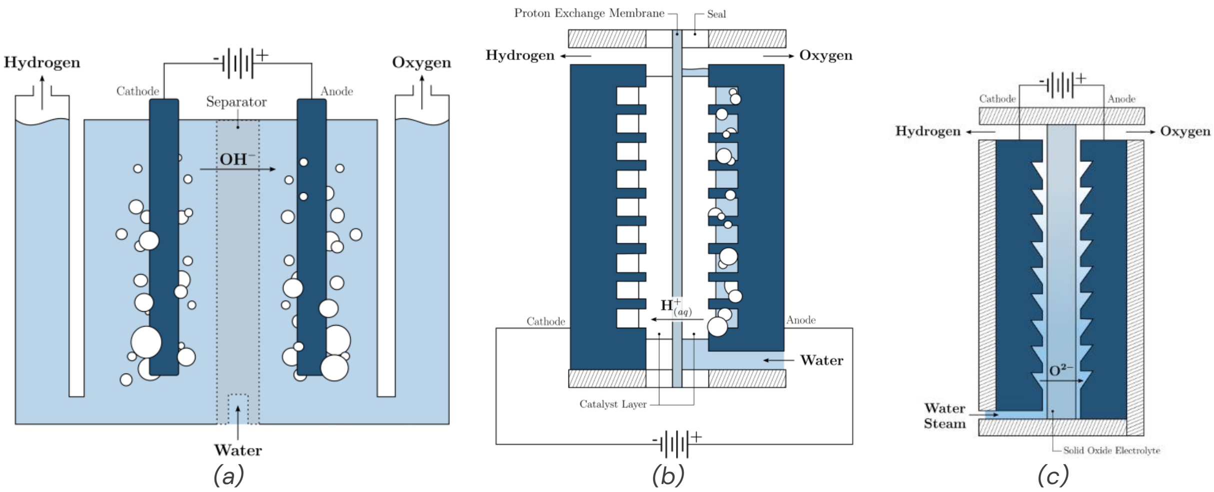

FIGURE 16: TYPES OF WATER ELECTROLYSIS. (A) AEL, (B) PEMEL, AND (C) SOEL [58].

The AEL is composed of two electrodes operating in an alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH) separated by a diaphragm enabling the separation of product gases and allowing the hydroxide ions (OH-) to move from one electrode to the other. The chemical reaction in each half-cell of the AEL is summarized in the first row of Table 4.

The PEMEL working principle is like AEL but with polysulfated membranes used as an electrolyte (proton conductor) with the water inlet on the anode side. The water reacts at the anode to form oxygen and positively charged hydrogen ions (protons) that move across the membrane to the cathode. The chemical reaction is summarized in the second row of Table 4.

The SOEL use a solid material as the electrolyte that conducts negatively charged oxygen ions to the anode, fabricated from strontium-doped lanthanum (LSM), forming oxygen gas, and generating additional electrons for the external circuit. The water inlet is on the cathode side, made of nickel/yttria-stabilized zirconia, that splits water into hydrogen gas and oxygen anions when a voltage is applied to the SOEL. The chemical half-cell reaction is summarized in the third row of Table 4.

TABLE 4: HALF-CELL REACTIONS OF THE DIFFERENT TYPE OF WATER ELECTROLYSIS.

	Cathode reaction	Anode reaction
AEL	$2H_2O + 2e^- \rightarrow H_2 + 2\,OH^-$	$2\,OH^- \rightarrow 0.5\,O_2 + H_2O + 2e^-$
PEMEL	$2H^+ + 2e^- \rightarrow H_2$	$H_2O \rightarrow 2H^+ + 0.5\,O_2 + 2e^-$
SOEL	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$O^{2-} - 2e^- \rightarrow O_2$

In Table 5 Table 5some key performance indicators are shown based on the reported values in [58].

TABLE 5: ELECTROLYSERS PERFORMANCE-RELATED CHARACTERISTICS.

	Op. Temp. (°C)	Op. Pressure (bar)	Power density (mW/cm^2)	Efficiency (%)	Lifetime (k.hours)	Capital Cost (€/kWh)
AEL	40-90	<30	<1	51-60	60-120	740-1390
PEMEL	20-100	<200	<4.4	46-60	60-100	1300-2140
SOEL	650-1000	<20	<3	76-81	8-20	>2000

Regarding the TRL levels for the stated technologies, SOEL maturity is still behind PEMEL and EAL, having a TRL of 4-5. PEMEL presents a TRL of 7-8 and EAL a TRL of 8-9.

1.3.2 Hydrogen Fuel Cells (HFC)

The fuel cell is an electrochemical device responsible for converting the chemical energy of a fuel into electricity though an electrochemical reaction. Fuel cells, from an electrochemical reaction point of view, are similar with electrolysers, though there are significant differences in their working principle and design – while electrolyser is designed for water splitting, the fuel cell is designed to combine reactants (*e.g.* oxygen and hydrogen) to produce electricity. Some of the most common fuel cells, are the alkaline fuel cell (AFC), proton-exchange membrane fuel cell (PEMFC), the solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), and the molten carbonate fuel cell (MCFC). The first three are illustrated in Figure 17 as examples that can be compared with the electrolysers.

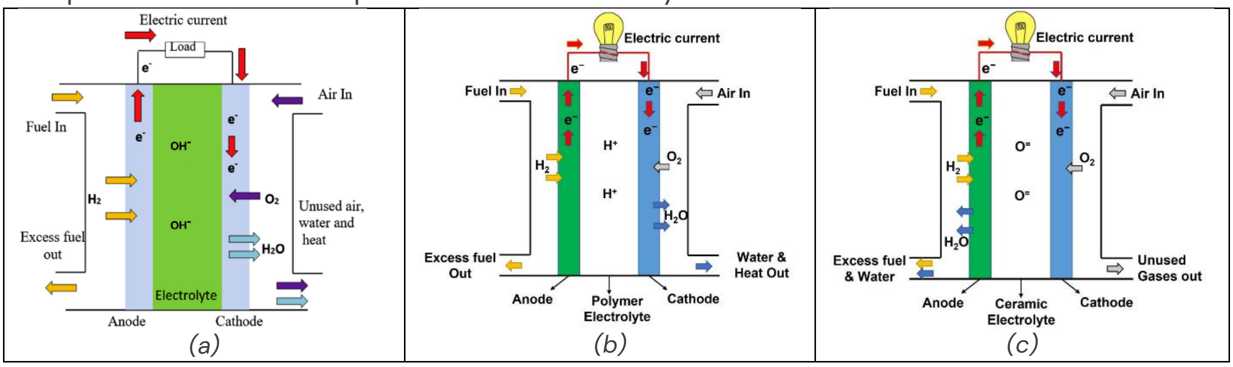

FIGURE 17: TYPES OF FUEL CELLS. (A) AFC [60], (B) PEMFC [61], AND (C) SOFC [61].

The AFC consists of a dual electrode, a gas diffusion layer (GDL), a liquid or polymer electrolyte and a catalytic layer. Humidified hydrogen gas is supplied to the anode, which reacts with the hydroxide ions in the electrolyte to produce water and electrons after penetrating the GDL and reaching the catalyst layer. A humidified oxygen source, typically purified air/oxygen is supplied to the cathode together with water. Oxygen gas, solvated in water, is reduced at the cathode catalytic layer to form hydroxide ions, which diffuse through the electrolyte to participate in the hydrogen oxidation reaction that takes place on the anode [60]. The resulting half-cell reactions are shown in Table 6.

The PEMFC consists of a dual electrode, a GDL, a PEM and a catalytic layer. Under the action of the anode catalyst, hydrogen molecules are converted into hydrogen ions. At the cathode of the PEMFC, after the air humidified by the humidifier, the humidified oxygen passes through the air flow channel of the cathode current collector to the cathode GDL. The oxygen in the cathode gas stream diffuses through the gas diffusion electrode towards the catalyst interface where it combines with the hydrogen protons and the electrons to form water [61]. The half-cell reactions are summarized in Table 6.

SOFCs use a solid ceramic electrolyte, such as zirconium oxide stabilized with yttrium oxide, instead of a liquid/polymer (used for alkaline cells) or aqueous membrane (used for PEMFC). The main components of planar SOFC are an anode, solid ceramic electrolyte, cathode, and bipolar separator plate. The molecular oxygen becomes oxide ions (O2-) and combines with hydrogen to form water while simultaneously producing electricity. The half-cell reactions are summarised in Table 6.

TABLE 6: HALF-CELL REACTIONS OF THE DIFFERENT TYPE OF FUEL CELLS.

	Cathode reaction	Anode reaction
AFC	$H_2 + 2\,OH^- \rightarrow 2H_2O + 2e^-$	$0.5\,O_2 + H_2O + 2e^- \rightarrow 2\,OH^-$
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$2H^+ + 0.5\,O_2 + 2e^- \rightarrow H_2O$
SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$O_2 \rightarrow O^{2-} - 2e^-$

In Table 7 some key performance indicators are shown based on the reported values in [61] for different fuel cell technologies.

TABLE 7: FUEL CELL PERFORMANCE-RELATED CHARACTERISTICS.

	Op. Temp. (°C)	Efficiency (%)	Lifetime (k.hours)	Capital Cost (€/kWh)
AFC	60-200	40-50	5-8	-
PEMFC	60-180	45-55	60-80	2370-2500 [62], [63]
SOFC	500-1000	50-60	20-80	-
PAFC	140-200	30-42	40-60	-
MCFC	650-800	43-55	15-30	-

Storing hydrogen is a big challenge in the hydrogen value chain since hydrogen is one of the smallest atoms known and presents a very low liquefaction point (-253 °C). Hence, there are four main forms of storing hydrogen: compressed hydrogen gas storage (g), geological hydrogen storage (g), liquified hydrogen (l), and material-based storage (l), as detailed in and summarized below.

Compressed hydrogen storage consists in storing the produced hydrogen in tanks at high pressure, between 350-1000 bar depending on the storing tank technology. The drawbacks of this storing method are the tank cost (highly increases with pressure) and the energy needed for pressurizing (around 10% of the stored hydrogen equivalent energy is spent in the pressurizing process).

Geological hydrogen storage makes use of existing geological structures, such as salt mines caverns or exhausted oil and gas fields, to store hydrogen in its gas form. It allows making use of the high volumes of the existing caverns for storing the hydrogen, making this storing method very appealing when large hydrogen plants are considered. Though it brings natural constraints regarding the geo-location of the facilities and system sizing, and challenges to ensure the cavern's hermeticity.
Liquified hydrogen consists in storing the produced hydrogen in liquid form in cryogenic tanks. Achieving so requires adding a liquifying stage, a process that usually requires both a lot of time and great amounts of energy (around 40% of the stored hydrogen equivalent energy is spent in the liquifying process). Even though, this form of storage allows to triple the energy density of storage, making it viable for high-demanding applications such as aerospace.
Material-based storage can be achieved in different forms:

- adsorption to store hydrogen on the surface of the material – hydrogen molecules or atoms attach to the surface of the material.
- absorption to store the hydrogen within the material – hydrogen is dissociated into hydrogen atoms that are incorporated into the internal solid lattice framework of a material.
- hydride storage which uses a combination of solid materials and liquid –uses the reaction of hydrogen-containing materials with water or other liquid compounds, like alcohols.

From the presented hydrogen fuel cell technologies, AFC and SOFC present the lowest TRL (between 7 and 8). PEMFC, PAFC and MCFC technologies are well established with several commercial solutions on the market. They present a TRL of 9.

To conclude, chemical energy storage presents several advantages compared to other storage systems, mainly related to the flexibility in supplying energy in the form of heat or electricity that can be transported in the form of chemical fuel. Though, it is clear that a P2P scenario results in significantly lower efficiencies since the storing and regeneration process involves several processes with currently low efficiencies (low round-trip efficiency) when compared to other energy storage systems.

1.4 COMPRESSED AIR ESS

In this chapter the concept of the Compressed Air Energy Storage is analyzed while a classification and a comparison among different technologies of CAES systems take place. The general concept behind energy storage system technologies is to store the excess energy, produced by conventional or renewable energy sources and use it when required, in order to maintain the stability and flexibility of the power grid. The same applies to CAES system, whose operation will be described below. However, according to the literature, building an underground reservoir or cavern to store the compressed air and all the necessary equipment for a CAES system can be expensive, making it difficult to compete with other energy storage technologies [64].

Compressed air energy storage (CAES) is a technology, used to store energy in the form of compressed air. This technology typically uses the excess energy, coming from intermittent operation of different renewable sources to compress air that will be stored in high-pressure tanks or underground caverns. When the grid's demand is high, the previously stored compressed air will be expanded through a gas-fired turbine to generate electricity, balancing the grid and improving its reliability [65].
CAES is able to store very large amounts of energy over long time periods, providing a reliable and efficient source of energy. As depicted in Figure 18 below [66], a typical CAES system is comprised of the following primary components:
(1) compressors
(2) expanders
(3) air reservoirs
(4) combustor
(5) motor/generator
(6) controlling system
(7) other auxiliary equipment such as fuel tanks and pipelines

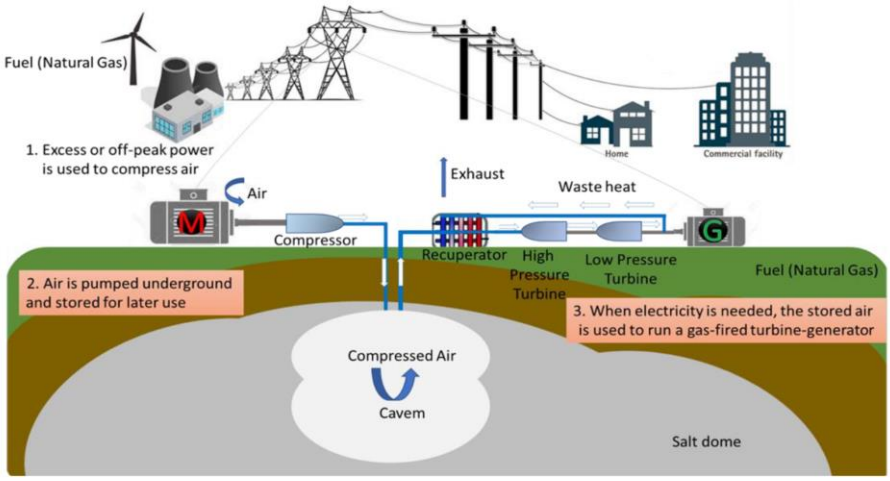

FIGURE 18: *COMPONENTS OF THE CAES SYSTEM* [66].

Compressed Air Energy Storage System (CAESS) is a technology that stores energy in the form of compressed air to be used later when needed. This system typically consists of three main components: a compressor, a compressed air storage, and a compressor/expander. The basic principle behind a CAESS is that energy is stored in the form of compressed air in an underground or above-ground compressed air storage, which is then released to generate electricity during periods of high demand.
In a typical CAESS, the energy is first converted into mechanical energy by driving a compressor that compresses the air and stores it in a high-pressure vessel, typically ranging from 350 to 1300 pounds per square inch (psi) [67].
As shown in Figure 19, CAES systems can be classified into three categories at different levels of development, based on the advantages and disadvantages of each technology, that cover a wide range of applications. More specifically, the primary categories include diabatic CAES, adiabatic CAES, and isothermal CAES. This categorization depends on the target of each

process and the main principle is the way that heat is handled during compression and prior to expansion of the air [66], [68].

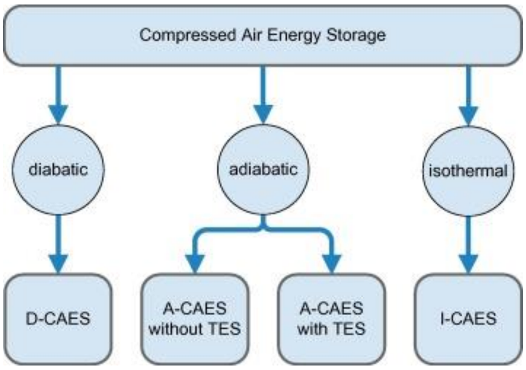

FIGURE 19:COMPRESSED AIR ENERGY STORAGE CONCEPTS CLASSIFIED BY THEIR IDEALIZED CHANGE OF STATE: (D(DIABATIC)-, A(ADIABATIC)-, I(ISOTHERMAL)-CAES) [68].

In the diabatic compressed air energy storage system (D-CAES), the heat of compression is rejected to the environment. External energy sources can be used to compensate for the wasted energy and reheat the air before the expansion. So, adiabatic compressed air energy systems (A-CAES) are being developed so as to address this issue. More specifically, these systems heat the air during the expansion process, increasing the overall efficiency of the system by reducing the amount of energy lost as waste heat. The isothermal compressed air energy storage system (I-CAES) is an emerging technology that aims to overcome some of the limitations of traditional CAES (diabatic or adiabatic). The main principle of I-CAES is the fact that air is compressed at a constant temperature. Consequently, the amount of energy lost as waste heat during the compression process is reduced, resulting in higher energy efficiency. The technical properties of the 3 aforementioned Compressed Energy Storage System technologies are summarized in Table 8below [65].

TABLE 8: COMPARISON OF VARIOUS CAES TECHNOLOGIES [66].

CAES Technology	Round-Trip Efficiency (%)	Temperature (°C)	Pressure in Cavern/Tank (MPa)
D-CAES	42-54	Max 1050	Max 7.2 Min 4.2
A-CAES	40-50 (Max 70-75)	Max 400	Max 6.6 Min 4.6
I-CAES	80 (Theoretically 100)	Constant	Max 1

Abbreviations: D-CAES, Diabatic Compressed Air Energy Storage; A-CAES, Adiabatic Compressed Air Energy Storage; I-CAES, Isothermal Compressed Air Energy Storage

The Huntorf facility is a ground-breaking engineering achievement and the first compressed air storage/gas turbine power station in the world, as it is operating since 1978. After a brief time of commissioning, the plant began operating, exceeding the design parameters (operational turbine period). The cavern plant was able to run smoothly for over 20 years after replacing the initial steel production strings with FRP ones after a few years. Moreover, this plant offers an output of around 300 MW, containing two caverns with a total tank capacity of 310.000 m^3 [69].

In 1991, the Alabama Electric Cooperative constructed the 110 MW McIntosh facility on the McIntosh salt dome in southwest Alabama. It utilizes a single salt cavern (560,000 m3) designed to operate between 45 and 74 bar and was built for 26 hours of continuous operation at full power. Dresser-Rand developed the project, but many of the operational elements of the plant (inlet temperatures, pressures, etc.) are identical to those of the Huntorf plant. However, the facility includes a heat recuperator, which lowers fuel consumption by approximately 22% at maximum load output, as well as a dual-fuel combustor capable of burning oil, as an alternative fuel, in addition to natural gas [70]. In TABLE 9 a comparison of the technical characteristics regarding these two operational CAES facilities is presented.

TABLE 9: INFORMATION DATA ABOUT THE COMMERCIAL CAES FACILITIES [69]–[71]

Description	Neuen Huntorf, Germany	McIntosh, Alabama, USA
Manufactured	Browne Boveri	Dresser-Rand
Year of Operation	1978	1991
Power Rating (MW)	290	110
Change Time/Discharge Time (h)	8/2	40/46
Power Capacity (MWh)	1,160	2,640
Tank Capacity (m^3)	310,000 (2 caverns)	560,000
Heat Sources	Natural Gas	Natural Gas
Air Pressure (bars)	46-66	45-74
Total compressor flow (kg/s)	416	154
Compressor Power (kg/s)	104	96
Efficiency (%)	42	54
Initial Cost ($-2010)	167,000,000	65,000,000
Storage Cost ($/kWh)	143,966	24,621
Installation Cost ($/kWh)	520,25	590,91

CAES is a technology that can store and release large amounts of energy over long periods of time, making it suitable for supporting the integration of variable renewable energy sources. It is mature, reliable and has a long lifespan of up to 50 years, making it a stable investment for utilities and energy providers. However, it requires large investments for construction and maintenance, including the cost of drilling underground caverns for energy storage.
Although CAES has the potential to become a key component of a more flexible and resilient energy system, increasing the demand for energy storage solutions, there is a variety of both technical and economic reasons for their limited market uptake. The widespread use of CAES is hindered by their respective technical characteristics, operational requirements, and

installation difficulties. Those concerns and drawbacks of such systems are summarized, as follows:

- limited locations for CAES systems due to geological requirements.
- strong technological competition from other energy storage technologies, such as lithium-ion batteries and fuel cells.
- strong competition from other energy storage technologies in terms of cost.
- the efficiency of a CAES system is limited by energy losses during compression, storage, and expansion. These losses can result in a relatively poor overall system efficiency of around 50-70%.
- CAES systems can store energy for limited time, typically a few hours to a few days, which may not be sufficient to meet long-term energy storage needs.
- The operation of the compressors and turbines can generate noise and vibration, making it not suitable for urban installations due to the inconvenience caused to nearby residents.

2 HYBRID ESS TECHNOLOGIES IN I-STENTORE PILOTS

The world is increasingly looking for sustainable and renewable energy sources to reduce dependence on fossil fuels, which have a limited supply and contribute to climate change. One way to achieve this goal is by using hybrid energy storage systems (HESS), which combine different energy storage technologies to provide better performance, reliability, and cost-effectiveness.

A hybrid energy storage system is an energy storage system that combines two or more energy storage technologies. The main objective is to provide a more reliable and efficient energy storage system, which can be used for different applications, such as power system balancing, transportation, and islanded microgrids.

The HESS can store energy from different sources, such as wind, solar, or hydroelectric, and then use it when required. This makes it possible to provide a continuous and reliable energy supply, regardless of the availability of the primary energy source.

The main advantages of HESS are:

- Improved performance: By combining different energy storage technologies, HESS can provide higher energy density, longer life cycle, and faster response times.
- Increased reliability: HESS can provide a more reliable energy supply, as it can store energy from different sources, reducing the risk of power outages or blackouts.
- Cost-effectiveness: HESS can reduce the cost of energy storage by combining different technologies, which can lead to lower costs and higher returns on investment.
- Flexibility: HESS can be customized to meet specific energy storage requirements, making them suitable for different applications and settings.

HESS can be used in various applications, including renewable energy, transportation, microgrids and smart grids. In the renewable energies domain, HESS can store energy from renewable sources such as solar and wind power, making it possible to provide a continuous and reliable energy supply increasing system's overall robustness. In transportation, HESS

can be used in electric vehicles to provide a more efficient and reliable energy storage system, increasing the range and reducing the cost of ownership. In microgrids, HESS can be used to provide a reliable and flexible energy storage system, reducing the dependence on the main grid, and improving resilience.
HESS can allow new electrical services to appear in the market, these services are needed due to higher renewable energies penetration that reduce the whole system's inertia. Thus, HESS may contribute to operate the whole system in a safer and reliable way. Here are some of the most important services that HESS can offer [72]:

- Synchronous Inertia: Synchronous inertia is a measure of the kinetic energy stored in the rotating masses of generators in a power system. It helps to maintain stable frequency and voltage in the system and is an important factor in maintaining power system stability.
- Synthetic Inertia: Synthetic inertia is a technique that involves using power electronics to mimic the behaviour of synchronous inertia. This can be useful in systems that have a high penetration of renewable energy sources, which may not have the same level of synchronous inertia as traditional generators.
- Fast Frequency Response (FFR): FFR is a mechanism for quickly adjusting the output of generators in response to changes in system frequency. This can be important for maintaining a stable frequency in the power system.
- Frequency Containment Reserve (FCR): FCR is a reserve capacity that can be activated quickly to help regulate system frequency. It is typically provided by generators that are capable of ramping up or down quickly.
- Automatic Frequency Restoration Reserve (aFRR): aFRR is a reserve capacity that can be activated automatically in response to changes in system frequency. It is typically provided by generators that are capable of responding quickly to frequency changes.
- Manual Frequency Restoration Reserve (mFRR): mFRR is a reserve capacity that can be activated manually in response to changes in system frequency. It is typically provided by generators that are not capable of responding as quickly as aFRR generators.
- Replacement Reserve (RR): RR is a reserve capacity that can be activated to replace the output of a generator that has unexpectedly gone offline. It is typically provided by generators that are kept on standby and can be brought online quickly.
- Black Start: Black start is the process of restoring power to a system that has experienced a complete blackout. This typically involves using generators that are capable of starting without an external power source.
- Voltage/Var Control: Voltage/Var control is the process of regulating the voltage and reactive power (VAR) levels in a power system. This can be important for maintaining system stability and preventing voltage fluctuations that could damage equipment.

HESS can also contribute to improve distribution grid operation, providing services that include:

- Voltage regulation: Voltage regulation is achieved through the use of voltage regulators, which are devices that automatically adjust the voltage levels of a power system to keep them within a certain range. Voltage regulators work by measuring the voltage levels in a power system and making adjustments to the voltage as necessary. There are several different types of voltage regulators, including tap-changing regulators, which adjust the turns ratio of a transformer to regulate voltage, and electronic regulators, which use solid-state devices to regulate voltage. Additionally, some power systems utilize automatic voltage regulators, which are designed to provide voltage regulation even during times of heavy load or other system disturbances.

- Voltage unbalance mitigation: A voltage unbalance mitigation service is designed to detect and correct voltage imbalances in the electrical grid. This is achieved through a combination of monitoring, analysis, and correction techniques. Typically, voltage unbalance is caused by uneven distribution of loads across the grid, or by other factors such as faulty equipment or wiring. To address voltage unbalance, a mitigation service will first monitor the grid to identify any imbalances. This may involve the use of sensors, meters, or other monitoring equipment. Once an imbalance is detected, the service will analyse the data to determine the cause of the problem. This may involve identifying the specific loads that are causing the imbalance, or investigating the equipment or wiring that may be contributing to the issue.
- Congestion management: Important tool for ensuring that electricity is distributed efficiently and reliably to end-users. In many cases, congestion occurs when there is insufficient capacity in the distribution network to meet the demand for electricity. This can lead to reduced efficiency, increased energy costs, and even power outages. congestion management services are used to monitor and manage the flow of electricity through the distribution network. These services typically involve the use of advanced metering and monitoring technologies to identify areas of congestion, as well as sophisticated algorithms and controls to manage the flow of electricity with real-time data which can be used to help grid operators planning for future demand.
- Power smoothing: This service is designed to ensure that the flow of electricity through the distribution network remains stable and reliable, even during periods of high demand or low supply. One of the most important features is its ability to manage fluctuations in electricity supply. This can be especially important in areas where renewable energy sources, such as wind or solar, are being used to generate electricity. These sources can be highly variable and can create instability in the distribution network if not managed properly. By managing the flow of electricity more efficiently. To address this issue, power smoothing services use sophisticated algorithms and controls to manage the flow of electricity through the network. This may involve using energy storage systems to store excess electricity during times of high supply and releasing it back into the network during times of high demand. It may also involve dynamically adjusting the flow of electricity through the network in response to changes in demand or supply.

In conclusion, hybrid energy storage systems offer a promising solution to address the challenges associated with energy storage. By combining different energy storage technologies, HESS can provide a more reliable, efficient, and cost-effective energy storage solution, suitable for various applications. The adoption of HESS is likely to increase in the coming years as the world continues to move towards a more sustainable and renewable energy future.

The following subsections present the set of HESS that will be exploited under i-STENTORE. Their main characteristics are described, together with their most prominent advantages and barriers to their adoption.

2.1 PUMPED HYDRO STORAGE INTEGRATED WITH LI-ION BATTERIES AND VANADIUM REDOX FLOW BATTERIES

Vanadium Redox Flow Battery (VRFB) is a promising technology for energy storage, as it has a long-life cycle, high efficiency, and can store energy for extended periods. VRFB stores energy in two tanks containing vanadium electrolytes, separated by a membrane. During charging and discharging, the electrolytes flow through the membrane, generating electricity. The advantage of VRFB is its scalability, as the energy storage capacity can be easily increased by adding more electrolyte solution.

Li-Ion battery is another popular energy storage technology, with high energy density, long life cycle, and low self-discharge rate. Li-ion batteries are commonly used in portable electronic devices and electric vehicles. In HESS, Li-Ion batteries can be used to provide high power output, with a fast charge and discharge rate [73].

Pumped Hydro Production is a form of energy storage that uses excess energy to pump water from a lower reservoir to a higher one. When the energy is needed, the water is released, flowing down to a hydroelectric generator, which generates electricity. Pumped Hydro Production is an established technology, with high efficiency and long cycle life.

The HESS that combines VRFB, Li-Ion Battery, and Pumped Hydro Production can provide several advantages, including:

- Increased reliability: By combining different energy storage technologies, HESS can provide a more reliable energy supply, reducing the risk of power outages or blackouts.
- Improved performance: The combination of VRFB and Li-Ion battery can provide a more flexible energy storage system, capable of providing high power and long-duration storage. Pumped Hydro Production can be used to provide a quick burst of energy, with high efficiency and long cycle life.
- Cost-effectiveness: HESS can reduce the cost of energy storage by combining different technologies, which can lead to lower costs and higher returns on investment.
- Renewable energy integration: The HESS can be used to store energy from renewable sources, such as wind and solar power, making it possible to provide a continuous and reliable energy supply [74].

In conclusion, the HESS using VRFB, Li-Ion Battery, and Pumped Hydro Production can provide a reliable, efficient, and cost-effective energy storage solution, suitable for various applications. The adoption of HESS is likely to increase in the coming years as the world continues to move towards a more sustainable and renewable energy future.

This HESS has several advantages over using only VRFB or only Li-Ion battery for energy storage.

Firstly, using a combination of VRFB and Li-Ion battery provides a more flexible energy storage system. VRFB can store energy for extended periods, whereas Li-Ion batteries can provide high power output with a fast charge and discharge rate. By combining these two technologies, the HESS can provide both long-duration energy storage and high-power output, which is essential for various applications, including renewable energy, microgrids, and utility-scale energy storage [73].
Secondly, the HESS using VRFB, Li-Ion Battery, and Pumped Hydro Production can provide a more reliable energy supply compared to using only VRFB or Li-Ion battery. The combination of different technologies can provide a more resilient and redundant energy storage system, reducing the risk of power outages or blackouts. If one technology fails, the other technologies can continue to operate, providing a more reliable energy supply.
Thirdly, the HESS using VRFB, Li-Ion Battery, and Pumped Hydro Production can be more cost-effective compared to using only VRFB or Li-Ion battery. By combining different technologies, the HESS can provide a more efficient and optimized energy storage solution, which can lead to lower costs and higher returns on investment. Pumped Hydro Production, for example, is a cost-effective energy storage solution, with high efficiency and long cycle life [74].
Lastly, the HESS using VRFB, Li-Ion Battery, and Pumped Hydro Production can provide better renewable energy integration compared to using only VRFB or Li-Ion battery. The HESS can store energy from renewable sources, such as wind and solar power, making it possible to provide a continuous and reliable energy supply. By combining different energy storage technologies, the HESS can provide a more flexible and optimized energy storage solution, which is essential for the integration of renewable energy.
In conclusion, the hybrid energy storage system using Vanadium Redox Flow Battery, Li-Ion Battery, and Pumped Hydro Production can provide several advantages over using only VRFB or only Li-Ion battery for energy storage. The HESS can provide a more flexible, reliable, and cost-effective energy storage solution, suitable for various applications, including renewable energy, microgrids, and utility-scale energy storage.

2.2 MOLTEN GLASS THERMAL STORAGE LEVERAGING AN END-FIRED HYBRID REGENERATIVE FURNACE

Using molten glass for thermal storage leveraging an end-fired hybrid regenerative furnace is a promising and innovative approach for utilising energy from renewable sources. A hybrid glass furnace combines heating by natural gas and electric heating using electrodes inserted into the glass melt. This combination aims to best utilize the advantages of both furnace technologies and diminishing their drawbacks. The operational flexibility of conventional regenerative fossil-fuel furnaces is maintained, both in terms of output flexibility and cullet rate, which are known limitations of all-electric furnaces. The electric heating, however, opens new opportunities for the utilisation of energy from renewable sources – during peak renewable energy production, the percentage of electrical heating (boosting) is increased, and when the supply of electricity is lower, boosting is lowered and most heating comes from natural gas, making the furnaces' strain on the power grid minimal.

HRAS is currently in the process of replacing the existing regenerative furnace at one of its production facilities with an innovative hybrid regenerative furnace with a capacity of 170 mt/day. Typically, hybrid glass furnaces have up to 20 % of their energy demand met using electricity (boosting.) HRAS system aims to manufacture high quality container glass with an electric rate up to 45 % (3.6 MW). The new furnace will be coupled with an already installed 521 kWp PV rooftop power plant located on the roof of the production facility housing the furnace. This will enable the use of the furnace as an energy storage unit when the surplus energy from the PV plant is available. In case the surplus energy must be utilized fully in the furnace, the glass melt will be overheated by up to 35 K. The estimated thermal capacity of this approach is approximately 3 MWh.

The proposed storage system can also be used to store energy from other geo independent RES, which would achieve a higher carbon neutrality. To properly implement this, it must include a predictive control system, which will enable electric boosting manipulation without affecting the glass batch quality and furnace refractory material. The proposed energy storage system can easily be extended for the provision of auxiliary services for the electricity grid.

Load shifting is a strategy used to manage energy consumption by shifting the time of energy use from periods of high demand to periods of lower demand [75]. In the context of renewable energy sources in energy-intensive industries, load shifting involves adjusting the time when the industrial process uses electricity so that it aligns with the availability of renewable energy sources. Recently, a study on load shifting potential of basic industries was conducted in Germany. Five energy – intensive industries were studied: metal production, chemicals, cement, glass, and ceramics; and key processes were analysed with respect to their options to provide flexibility in the use of electricity. Out of the five industries, three include high temperature furnaces used as a heat storage medium. In the steel industry, the electric arc furnace was investigated. Electric arc furnaces are generally operated close to the upper production limit, making an increase in load impossible. A reduction in load without short term compensation would cause a reduction in production. In a continuously operated plant, one undisrupted work shift (8 hours) generates 20 minutes of potential for energy flexibility, since the production capacity for continuous casting is generally smaller than the production capacity of the electric arc furnace.

Production of synthetic raw materials using a melting furnace requires very high process temperatures (up to 3000 °C). Load shifting potential of an electric arc furnace for the production of corundum was investigated, and it was concluded that short – term negative flexibility with a notice period of 1 hour can be provided. Positive flexibility can be achieved as well, by reducing the electrical load or a short time turning – off the furnace [76].

In the German glass industry, about 75 % of all container glass production furnaces are equipped with an auxiliary electric heating device, which supplies approximately 5 – 15 % of the thermal energy demand. A variation in boosting is possible, with the changes in electric load being compensated for by respective adjustment of the thermal input from fossil fuel combustion. The German study concluded that deviations in the standard operating window are only possible within short time periods, since longer time periods are associated with major temperature variations, risking premature local corrosion damage on the refractory lining of the furnace [76].

The comparison of technical flexibility potentials for the electric arc furnace, raw materials melting furnace and container glass production in Germany are presented in Table 10.

TABLE 10: COMPARISON OF TECHNICAL FLEXIBILITY POTENTIALS FOR THE ELECTRIC ARC FURNACE, RAW MATERIALS MELTING FURNACE AND CONTAINER GLASS PRODUCTION IN GERMANY [76].

	Electric arc furnace	Container glass production	Raw materials melting furnace
Framework	Continuous cast plant at full capacity	Continuous production for up to 15 years and more	Operating at full capacity
Potential in Germany (Number of production units / Availability)	Positive: 766 MW Negative: - (26 / 52 %)	Positive: 25 MW Negative: 15 MW (45 / < 80 %)	Positive: 23 MW Negative: 3 MW (13 / 45 %)
Duration of recall	Several minutes	Minutes	Positive. 5 – 60 min Negative: 15 min
Frequency of recall	Several times a day	Up to several times a day	Several times a day
Characteristic attributes of the process	Availability for flexibility difficult to project	Variation of electrical load has to be compensated by input of fossil fuel	Continuous batch process

Load shifting in melting furnaces has also been explored in copper production. The demand response was analysed by optimising scheduling the batch and continuous tasks of a representative copper process. The annual cost of electricity was reduced up to 14,2 %, with no negative consequences on production goals. The average load shifted in a two-week schedule horizon was 2,55 GWh [77].

Besides the study of container glass production load shifting potential in Germany, there have not been a lot of investigations on load shifting in the glass sector. Recently, a physics – based model was developed to describe the dynamic behaviour of a prototype electric boosting glass furnace. Typically, boosting covers 5 – 20 % of the energy demand. In this study, a strategy to optimally balance between using natural gas and electric power under electricity price fluctuations was described. During high energy demand, boosting was lowered, and during energy abundance, boosting was increased. The proposed DR framework could significantly lower stress on the power grid. This model, however, was not applied practically on industrial examples, and bubble removal, homogenization, uncertainties in demand and furnace operation were not addressed [78].

Most load shifting studies in high temperature energy storage focus on shifting the load from peak demand to times when electricity is abundant with the goal of economic optimization. In all cases, the load shifting potential is limited by production demands, and the same goes for the glass sector. Our use case enables not only the potential for flexibility, but also for additional energy storage by overheating of the glass melt. Because of the overheating, the viscosity of the glass will change, which might affect the flow of the glass melt in the furnace. The effect of the changes will be closely monitored regarding the refractory material quality, end product quality, furnace operation, and energy efficiency. Higher glass melt temperatures because of increased boosting will lower crown temperatures, which will lower emissions of pollutants and alkali vapours. A decrease in the latter might positively affect the crown refractory material lifetime. Higher melt temperatures also mean lower gas consumption in feeders, as the melt will not need to be heated as much to reach the appropriate working temperature. Increased electric boosting will decrease overall natural gas consumption, lowering the CO2 footprint of the process.

The European container glass sector produced 23.458 thousand tonnes of glass in 2021, 14.779 thousand tonnes (63 %) of which came from end-fired regenerative furnaces [79], [80]. In sites with existing end-fired regenerative furnaces, the proposed technology can be applied without major interventions. This presents a major potential for load shifting in Europe. For example, if every facility implemented boosting with the possibility of overheating the glass melt up to 35 K (as in our use case), the resulting load shifting capacity of the glass sector would be approximately 1 GWh.

HRAS case will provide the answers to important questions about the effect of load shifting, glass melt overheating, and high percentage of boosting on furnace operation, glass quality, economic feasibility, refractory lifetime, and energy efficiency. This will enable easier and clearer implementation of similar systems in the glass sector, providing greater energy grid flexibility, while parallelly decreasing the carbon footprint of this energy – intensive process.

2.3 HYDROPOWER PLANT + WIND FARM + PV INTEGRATED WITH A VANADIUM REDOX FLOW BATTERY AND STORAGE FACILITY

One of the potential use cases regarding the hybridisation of energy storage technologies is the integration of a series of storage assets, namely a Vanadium Redox Flow Battery (VRFB) and a Li-ion (LIB) battery, in coordination with a manageable hydropower plant. This use case becomes even more relevant considering that the operation of the aforementioned assets takes into account the requirements of renewable power plants located on the same distribution grid, such as wind or photovoltaic plants. Therefore, this solution allows the optimisation of the available storage resources, finding the best combination to cope with the inherent intermittency of renewable generation, while being able to provide different services to both the transmission and distribution grids.

In recent years, VRFBs have become one of the best options for large-scale stationary applications due to a number of particularly favourable characteristics. In these batteries, energy and power are decoupled, as the energy storage capacity depends on the concentration and volume of the electrolyte fluid, while the power rating is defined by the characteristics of the cells in the stack, resulting in a high degree of flexibility [81]. Due to its scalability, the storage of large amounts of energy is technically feasible, but also beneficial from an economic and marginal cost reduction point of view. Consequently, these batteries are suitable for use cases that require several hours of storage, such as the arbitrage of large amounts of energy. Notwithstanding, their dynamics are also appropriate for short-term high-power applications. VRFBs offer a long cycle life and a long overall lifetime, and these characteristics are not significantly affected by a high depth of discharge [82]. Thus, low degradation is an additional advantage.

On the other hand, Li-ion batteries, which are widely implemented in portable systems and electric vehicles owing to their high power and energy density, are increasingly being used in stationary applications to provide different services to the grid, taking advantage of the price reduction trend that has taken place over the last decade and is expected to continue [83], despite some circumstantial increases due to geopolitical events. Fast charging, high round-trip efficiency, high reliability, and fast response times are just some of the features that make this technology suitable and flexible for power and energy applications. In the technical literature, it can be found that this technology is commonly used to support frequency regulation in short periods of time [84], [85]. Nevertheless, proper control and monitoring of battery operating conditions is essential to avoid premature deterioration and to extend the cycle life, while also estimating battery internal states. In comparison with VRFBs, a high depth of discharge leads to degradation and reduces its overall lifetime [86].

Depending on the sizing and the services to be provided, both technologies may display specific characteristics that can make them more suitable and economically advantageous [87]. For that reason, the hybridisation of a VRFB and a Li-ion battery is a solution to be considered in order to complement each other in terms of power and energy applications, durability, and cost-effectiveness.

The integration of both technologies in a Hybrid Energy Storage System (HESS) allows the application of optimisation techniques that can consider the technical constraints of both assets, depending on the required services, as well as the minimisation of the cost of use. This cost must take into account the efficiency and degradation of the system, which could be assessed by applying degradation models [88].

According to [9], the optimisation of this HESS can be based on finding the optimum between the degradation of the Li-ion battery and the ohmic losses and parasitic losses caused by electrolyte circulation that take place in the VRFB. The latter could be particularly relevant when charge/discharge power is low, reducing the overall efficiency of the system. These algorithms can be implemented as part of a combined energy management system that can balance between minimising degradation and maximising efficiency.

The VRFB-LIB HESS is interesting in a wide range of applications, ranging from isolated systems [89] and microgrids [90] to integration into transmission and distribution grids, supporting their stability, reliability and enhancing their capacity to handle variable renewable generation. This HESS has been adopted as the solution in projects in different areas: the "BiFlow" project in Bruchsal, Germany, proposes this HESS to supply heat and power to a student residence and to provide charging for electric vehicles [91]; in the Monash Microgrid, Australia, a 120 kW/ 120 kWh Li-ion battery is integrated with a 180 kW/900 kWh VRFB, using the former for short-term high-power applications and the latter for long term energy requirements [92]; and in the Superhub Oxford Project, in the United Kingdom, this HESS has been installed in the transmission grid. In this project, a hybrid battery consisting of a 50 MW Li-ion battery and a 2 MW/5MWh vanadium flow battery, sited at National Grid's Cowley Substation, is used to provide services to National Grid and to trade in different energy markets [93]. All these studies and projects emphasise that the use of a hybrid solution improves the global efficiency and reduces the degradation of the Li-ion battery, thereby increasing the overall lifespan of the system.

The proposed use case not only combines these two batteries, but also integrates a manageable hydropower plant. Hydropower plants transform the potential energy of water into electrical energy and can be divided into run-of-river and regulated power plants. In the latter, a large amount of water is stored in a reservoir, and its management allows long-term energy storage. In addition, it is possible to store large amounts of energy and the power that can be developed by the turbo-generator group is very high. In general, the levels of stored energy and developed power can be much higher than those associated with battery storage. On the other hand, even if hydropower plants present fast dynamic response, the response times of batteries will generally be even shorter. These features enable both technologies to complement each other and take advantage of their particular benefits.

Furthermore, the interest of this use case also lies in the fact that while the assets are connected on different nodes distributed over an electrical area, the application of a set of communication protocols and hierarchical control architectures allows them to be aggregated and operated as a single Virtual Energy Storage System (VESS). This VESS can support grid operation according to the requirements of the Distribution System Operator (DSO) and provide storage services to renewable power plants associated with it, namely a wind power plant and a photovoltaic plant, considering the market conditions as well. This architecture is shown schematically in Figure 20.

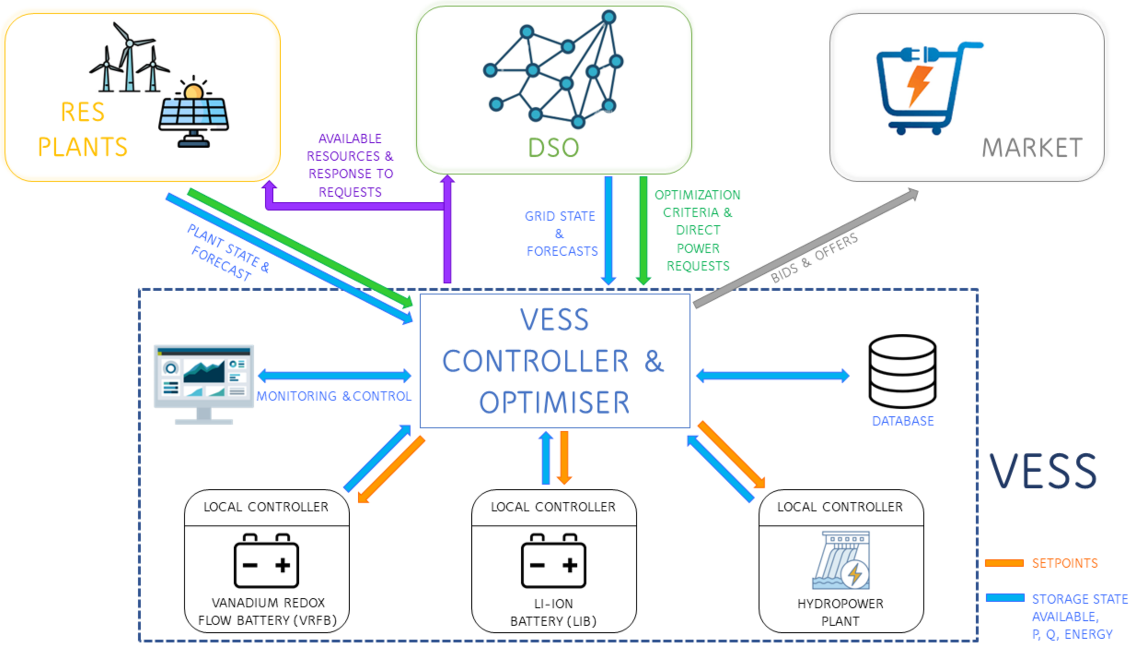

FIGURE 20: VESS ARCHITECTURE.

The various benefits of battery hybridization previously discussed are once again applicable. The VESS platform can incorporate optimisation procedures that take into account the technical constraints based on the sizing, capabilities, dynamics, and characteristics of the assets, as well as their marginal costs. Thus, it may also be feasible to integrate the management of the hydraulic resource and the minimisation of undesirable effects in the hydropower plant, such as electromechanical coupling events that may arise in its response, potentially leading to degradation of the hydraulic turbine and generator mechanical train. In addition, grid power flow optimisation could also be applied.

This algorithm can be executed in different time frames. On the one hand, optimised operation schedules will be generated for each asset, resulting from their participation in the energy markets and the scheduled services to be provided to the DSO and the renewable power plants.

On the other hand, there must be real-time information exchange between the VESS assets, as well as with the DSO's SCADA and the renewable power plants, so that the planned scheduling is adapted to real-time operating conditions.

This architecture is implemented through local controllers at each component of the VESS, which act as their own energy management systems and interact with the global VESS controller & optimiser.

In conclusion, the hybridisation of different technologies and their integration into an interconnected Virtual Energy Storage System offers numerous advantages over operating them as individual assets.

Firstly, the control, management and optimisation schemes that can be applied lead to a better performance of the resulting configuration, exploiting the most favourable characteristics of each asset and overcoming the limitations of a single technology. It is therefore possible to extend the lifetime of the global system and increase its efficiency, which also implies a reduction in the cost of use. In addition, the diversification of the storage resources increases overall reliability.

Secondly, the resulting VESS offers higher flexibility, enabling the participation in energy markets, developing applications such as arbitrage, which holds high economic value and potential for return on investment.

Thirdly, the fact that the VESS assets are connected on the same area of the grid and interacts with the DSO's SCADA allows a coordinated and coherent response to possible contingencies. This way, the VESS can provide different flexibility and ancillary services such as congestion mitigation, frequency regulation, voltage regulation, system restoration and inertia emulation, which also results in improved power quality.

Finally, the VESS allows a greater penetration of renewable generation, contributing to the management of its variability by providing services such as capacity firming or peak shaving. Furthermore, renewable power plants have access to storage services despite not having them installed in their own infrastructure owing to the direct interoperation with the VESS. This feature allows the VESS assets to be installed in the most optimal locations on the grid.

2.4 ELECTROCHEMICAL BATTERY INTEGRATED WITH SUPERCAPACITOR

As explained above, batteries feature high energy density but low power density, additionally, they have slow charging and discharging rates. On the contrary, supercapacitors can charge

and discharge quickly but have a lower energy density and cannot store as much energy as batteries. Therefore, to overcome the limitation of both technologies, hybrid electrochemical energy storage systems (HEESSs) aimed at integrating electrochemical batteries and supercapacitors appear as promising solutions [94]. Indeed, the combination of these two technologies results in a more efficient and versatile energy storage system. This hybrid solution enables quick and efficient energy transfer while also providing the capability to store large amounts of energy. Furthermore, hybrid storage systems represent a suitable solution to increase the lifetime of batteries by reducing the number of charge-discharge cycles required [95], which can result in significant cost savings. Overall, the combination of batteries and supercapacitors in hybrid storage systems offers a promising solution to meet the growing demand for high-performance energy storage systems.
With this regard, HEESSs are widely adopted in electrical vehicle (EV) applications and smart grids. EVs are subject to recurrent current spikes caused by traffic, road conditions, driving styles, and other factors that significantly impact battery lifespan [96]. Thus, to mitigate peak currents and enhance battery life, combining a battery pack with a supercapacitor pack is becoming a prominent solution [97].
On the other side, smart grids aim at effectively integrating Renewable Energy Sources (RESs), i.e., solar and wind, whose unpredictable and intermittent nature makes their integration into power systems very challenging [98]. Hence, batteries are accepted as one of the most important and efficient ways to stabilize electricity networks [99]. However, in a typical microgrid, the batteries experience irregular as well as frequent charging/discharging phases that lead to a rapid decay of their lifetime, resulting in ineffective several replacements [100]. Thus, HESSs represent a suitable solution to address the challenges introduced by RESs [101].

Generally, according to their configurations, hybrid storage systems are classified into three categories: passive, semi-active and full-active topology [102].
The passive topology is the simplest as well as cheapest solution. As shown in Figure 10 it does not require any DC/DC converter, the supercapacitor and the battery are connected in parallel to the DC bus, so their voltages must be identical. This topology offers several advantages, including low cost, size, and weight. However, there are no converters, so the supercapacitor voltage cannot be effectively controlled and remains fixed to the battery voltage [4]. This structure has no degree of freedom, indeed no algorithm can be applied for the management of the power sources, whose charge/discharge is governed by their internal resistances. As a result, this configuration cannot fully exploit the main benefits of the supercapacitor, which acts mainly as a low-pass filter.

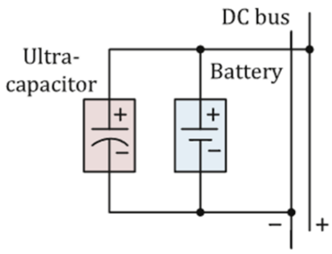

FIGURE 21:PASSIVE HYBRID ENERGY STORAGE SYSTEM [103].

Figure 21 shows two different configurations for the semi-active topology. This solution employs a single converter connected in series to only one of the two power sources, whereas the other is directly connected to the DC bus. In case (a) a bidirectional DC/DC convert controls the power exchanges between the DC bus and the battery, while the supercapacitor absorbs significant current fluctuations. However, this configuration's primary drawback is the direct connection of the supercapacitor to the DC bus, which leads to significant voltage fluctuations [104].

With this regard, configuration (b) overcomes the above-mentioned limitations, indeed the bidirectional DC/DC converter connected in series with the supercapacitor allows exploiting the wide-voltage range of the latter while keeping the DC bus voltage stable because of the direct connection to the battery [103].

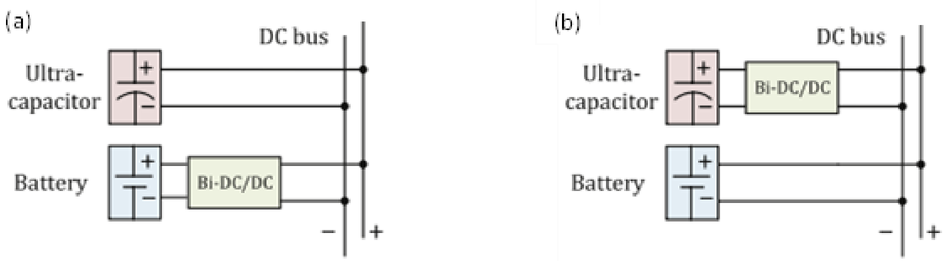

FIGURE 22: SEMI-ACTIVE HYBRID ENERGY STORAGE SYSTEM TOPOLOGY: (A) BATTERY SEMI-ACTIVE TOPOLOGY (B) ULTRA-CAPACITOR SEMI-ACTIVE TOPOLOGY [103].

The full-active hybrid energy storage system (shown in Figure 23) controls both the battery and supercapacitor using power converters. The power sources are entirely decoupled from the DC bus, offering a high level of controllability. However, compared to the semi-active topologies, this configuration entails higher power losses, size, weight, and costs due to the need for more converters [105].

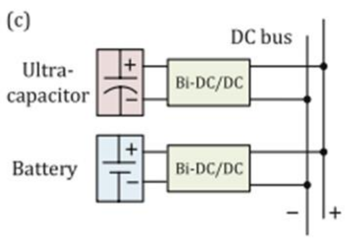

FIGURE 23: FULL-ACTIVE HYBRID ENERGY STORAGE SYSTEM TOPOLOGY [103].

Finally, as a compromise between the cost and complexity of the control strategy, a semi-active topology is usually selected as the optimal topology [106].

2.5 WINDPOWER + PV PLANT + ELECTROLYSER + LI-ION BATTERY + H2 STORAGE

The hybridization of renewable energy systems has proven to be a reliable and cost-competitive option for power generation from renewable resources [107]. Hybrid renewable energy systems (HRES) result from the combination of more than one energy source with the objective of optimizing the synchronicity and power output with the power demand profile from the grid or the stand-alone applications. The combination of several energy sources compensates the highly variable nature of the power outputs to produce a more reliable power output [108] and has been adopted as a result of the efforts to increase the renewable energy penetration in the global power plant mix. In electricity generation, the two most common configuration of HRES is the combination of solar photovoltaic and wind power (PV/WD HRES) [109]. The power output of a hybrid solar PV plant and wind power generation was proved to be more reliable than operating them individually [110]. Furthermore, nowadays, both technologies present high levels of readiness maturity and benefit from a highly developed global market and supply chains which reduces drastically the levelized cost of energy produced by these technologies and makes them highly attractive for investment. However, even combined, the variable nature of renewable energy generation imposes complex technical management challenges and associated caused by its stochasticity and consequent forecast errors. The engineering design process of less or more complex hybrid systems must concern the reduction of loss of load risk considering the local production constraints such as the latitude and climate region where the sites are located. One important feature to be considered in order to maximize the usage of renewable resources and avoid a mismatch between energy demand and supply is the usage of energy storage systems (ESS) as a solution to compensate the power output imbalances [111]. Storage capacity can be used to improve wind power curtailment effectively and use the higher predictability [112] of solar PV production for peak-shaving and load balancing, for example. ESSs in support of HRES can however be further operationalized by targeting ancillary services and other energy markets like flexibility, as discussed before in the document, then just providing balancing grid services for DSOs and TSOs. Therefore, manageable ESSs installed directly in wind farms and PV plants as balancing reserves have the potential to optimally maximize the penetration of non-renewable-dispatchable renewables and their profitability [113],[114].
Like the technological hybridization of the production side, the storage systems supporting RES production are more versatile and efficient if several technologies are combined. In this scope, several studies, and demonstrators [108] assessed the suitability of hybrid energy storage systems associated with PV/WD HRES can provide unique advantages in improving the system performance and generating new revenue streams in off-grid, micro-grids, and utility-scale scenarios. The combination of a Li-ion Battery, power-to-hydrogen via electrolyser, and hydrogen storage, showed to be specifically advantageous if, in addition to the electricity market, a local hydrogen market is deployed or planned, to provide services for heating, transportation or even for electric power generation using fuel cells.

The HESS combining Li-Ion Battery and Hydrogen (electrolyser and hydrogen storage tanks (HST)), can provide several advantages when associated to an PV/WD HRES, benefiting from the wide spectrum of capabilities offered by the different technologies in terms of power, storage periods and life cycles contributing and improving to the reliability and performance of the system operation and the local grid, and ultimately increasing the return on investment of the overall system.
The grid-forming capabilities of high-capacity Li-Ion battery energy storage systems make them suitable to act as a Virtual Power Plant, providing:

- grid frequency and voltage regulation services, which particularly important in remote grids where PV plants and wind farm are usually connected.
- inertia emulation, power oscillation damping, stability/passivity for the active system.
- smooth black-start and islanding effect, e.g., in the case of a failure in the main grid, the system allows the HERS to continue providing energy to an isolated grid, while guaranteeing a smooth subsequent resynchronization of the electrical island to the main grid.
- congestion management.
- power smoothing and load shifting.
- cost-effective local hydrogen production.
- capability to integrate new local charging processes to the system, as EV's high efficiency ultra-fast charging (V2G and B2V), while ensuring high quality and beneficial interaction with to grid needs through the use of technologies such as V2G and B2V.

In a HESS configuration, electrolysers are usually combined with high pressures hydrogen storage tanks minimizing energy losses of the RES production, while increasing the revenue streams of the power plant by storing hydrogen when any surplus occurs or in the case of the local hydrogen market is more appealing than the energy injection to the grid. The hydrogen market is extensive and highly valorised. The stored hydrogen is mainly used as an energy vector for hydrogen-fuel cell vehicles, or other hydrogen-to-power applications. It can also be used to increase gas volume distribution by diluting it with the gaseous hydrocarbon to be used as e-fuel in transportation, heating and power generation. Other common applications are several other industries that uses it as raw material or energy (heat source), such as petroleum, chemical, electronics, metallurgy, aerospace, light industry, and other fields [115].

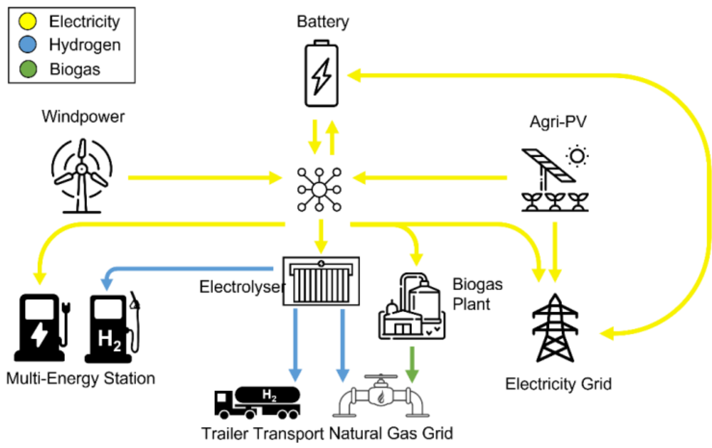

FIGURE 24: SCHEMATIC DIAGRAM OF THE HYBRID STORAGE SYSTEM COMBINING WINDPOWER, APV, A UTILITY-SCALE LI-ION BATTERY AND GREEN H2 PRODUCTION AND STORAGE

In the scope of the i-STENTORE project (Figure 24), it will be implemented a HESS combining an Agri-photovoltaic solar plant [116], [117] and a wind turbine, with the respective nominal power of 3 MW and 4.2 MW, associated with a 3MW hydrolyser and a high capacity 1MW/1MWh Li-Ion BESS. The BESS will be managed maximizing the production of green energy using renewable electricity produced by the PV/WD HRES to power the hydrolyser while offering advanced ancillary services (grid-forming) and flexibility to the distribution grid operator and bringing new dynamic functionalities to improve the security of supply of the APV plant associated processes. The green hydrogen produced will be used as fuel in a multi-energy station combining EV supercharging, covering Vehicle-to-grid (V2G) functionalities into operation and regulation services useful to the local system operator. Furthermore, it is planned to explore another hydrogen market vector in synergy with a local natural gas production plant to increase the throughput volume by combining to the already gasification capacity with the dilution of up to about 15% of green hydrogen.

2.6 OVERVIEW OF I-STENTORE HESS CAPABILITIES TO PROVIDE ANCILLARY SERVICES

TABLE 11: ANCILLARY SERVICES OVERVIEW

		Demo 1		Demo 2		Demo 3		Demo 4		Demo 5	
		Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE
Transmission	Synchronous Inertia	🔴	✘	🟢	✔	🟢	✘	🔴	✘	🟢	✓
	Synthetic Inertia	🟡	✘	🟢	✘	🟢	✘	🔴	✘	🟢	✓
	Fast Frequency Response	🟡	✘	🟢	✔	🟢	✔	🔴	✘	🟢	✓
	Frequency Containment Reserve	🟡	✘	🟢	✔	🟢	✓	🔴	✘	🟢	✓
	Automatic Frequency Restoration Reserve	🟡	✘	🟢	✔	🟢	✓	🔴	✘	🟢	✓
	Manual Frequency Restoration Reserve	🟡	✘	🟢	✘	🟢	✓	🔴	✘	🟢	✓
	Replacement Reserve	🔴	✘	🟢	✘	🟢	✘	🔴	✘	🟢	✓
	Black Start	🔴	✘	🟢	✘	🟢	✘	🔴	✘	🟢	✓
	Voltage/Var Control	🟡	✘	🟢	✘	🟢	✘	🔴	✘	🟢	✓
Distribution	Voltage regulation	🟡	✘	🟢	✘	🟢	✔	🟡	✘	🟢	✓
	Voltage unbalance mitigation	🟢	✘	🔴	✘	🟢	✘	🟢	✘	🟢	✓
	Congestion management	🟢	✔	🟢	✘	🟢	✔	🟢	✔	🟢	✓
	Power smoothing	🟢	✔	🟢	✔	🟢	✓	🟡	✔	🟢	✓

3 ANALYSIS OF ENERGY STORAGE DEPLOYMENT BARRIERS – TECHNOLOGICAL, ECONOMIC AND SOCIETAL BARRIERS

The energy system is undergoing a profound transformation in response to the EU's ambitious carbon-neutrality targets for 2035 and 2050, but also to become more secure and resilient to rapidly changing geopolitical scenarios. The challenges are posed by a growing share of renewable energy sources, more and different players in the energy markets, and increasingly decentralised systems that will need to be digitally interconnected. However, the challenge of energy diversification and the acceleration of renewable energy penetration also brings new opportunities, namely in the management structure of future energy systems. Distributed renewable energy production requires greater system flexibility to adapt to changing grid needs and the ability to manage variability and uncertainty in demand and supply over all relevant timescales. Furthermore, the changing patterns of energy production and consumption require more ancillary services to ensure system stability and reliability, and ultimately security of energy supply. It is in this scenario that energy storage plays a key role, by providing the necessary flexibility, stability, and resilience to the power system. Despite of the diversity of energy storage technologies available most of them still have a long path to achieve the capacity levels necessary in accordance with its specific potential role to attend and to continue following the high penetration rate of renewable energy generation in the system. The rapid pace required for the development of the energy storage market contrasts with the natural and common obstacles to any rapid technological deployment, such as creating an appropriate regulatory framework and developing proper business models *to exploit the technological solutions in the specific markets. The development of sustainable storage business models is constraint by the societal perception of usefulness, safety and impact of the available technologies and most of all if the revenue stacking relies on services in an extremely volatile market. In particular, the revenue streams should focus on flexibility services for distribution networks and the provision of ancillary services. Nevertheless, the business models are strictly dependent on technologies' characteristics and specific applications. Furthermore, the high initial capital investment of storage facilities requires reasonably secure and predictable long-term revenues to ensure its economic viability. Identifying and properly assessing these barriers is crucial to developing sustainable business models.

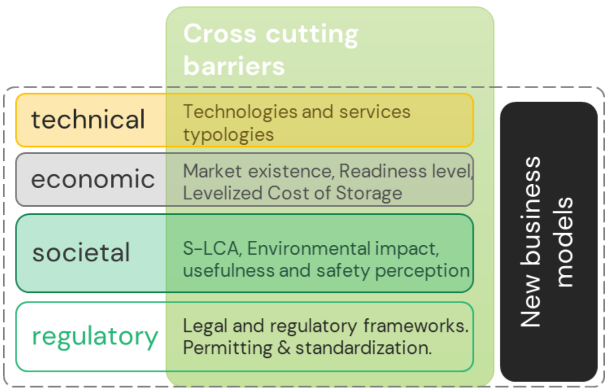

FIGURE 25 MAIN BARRIERS TO STORAGE DEPLOYMENT.

This section intends to identify and categorizes the main barriers for the integration energy storage systems in addition to the ones imposed by the regulatory framework previously addressed. The prominent barriers to storage deployment can be grouped as following:

- Technical barriers
- Market design barriers
- Societal challenges

3.1 TECHNICAL BARRIERS

The wide range of energy storage systems available on the market are of various technological natures comprising mechanical, electrochemical, electrical, chemical, and thermal energy storage systems. Each technology has its specificities and therefore different applications that vary depending on technical parameters as the level of storage capacity, duration of storage and associated losses, speed of charge and discharge which defines its adequacy for a particular field of application as for providing different services to the power grid. However, the several technologies do not present the same level of maturity, which in some cases may represent a usage barrier with respect to the cost, reliability, and safety. The storage technologies are still underdeveloped at different paces, from research level, deployment or in commercial stages.

3.1.1 Technological maturity and adequacy

The technology readiness level, TRL, defined in Horizon 2020 2014-2015 Work Programme, is an effective instrument to rank technologies accordingly with the stages of development. An extended readiness level assessment of storage technologies was published recently by the EU Energy Transition Expertise Center [118] and the summary result in shown Figure 26. In a first analysis, it can be concluded that among the main technological groups, identified by different colors, most technologies are above TRL 5, which means that they were validated in an industrially relevant environment, and most of them were effectively demonstrated (TRL 6), expressing the high level of investments in the recent decades in research and development of energy storage. All main groups show subcategories as well that were actually proven in operational environment; from those the ones that reached the commercialization phase had to resist to the market entrance till they reach acceptable levelized costs of storage (LCS) becoming attractive for investment. However, research and development for many of the categories are still in early stages, with particular emphasis on thermal and electrochemical storage technologies. Thus, a continuous effort on energy storage should be expected in the following years, targeting capital and operating costs reduction, and to enhance the technical parameters expanding the fields of application.

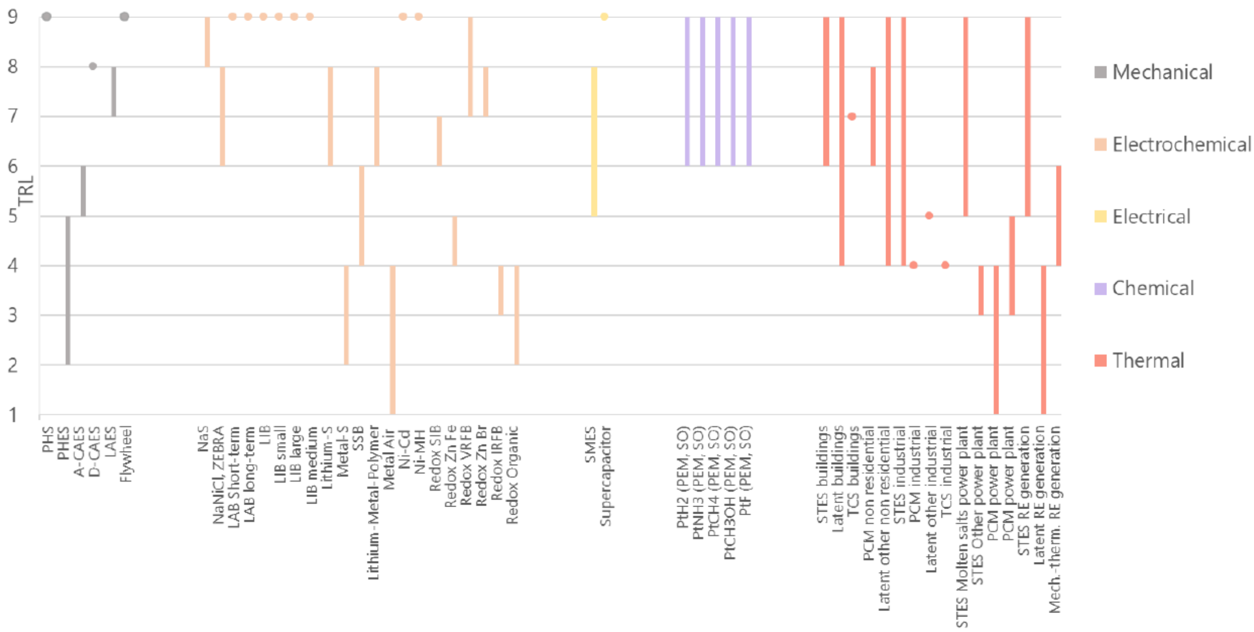

FIGURE 26: TECHNOLOGY READINESS LEVELS (TRLS) OF ENERGY-STORAGE TECHNOLOGIES. THIS FIGURE IS TAKEN FROM [118].

The wide portfolio of available energy storage technologies allows the development of an equally extended portfolio of applications towards a more decarbonized, reliable, and secure energy system.

Energy storage systems are essential to follow with fast growing renewable energy resources penetration, introducing flexibility to the system to better satisfy the grid requirements, with a central role on network-congestion-relief by absorbing locally generated renewable electricity. The adoption of ESS can replace the needs of infrastructure upgrades of transmission and distribution networks, and also facilitates the electrification of isolated areas or where the infrastructure is weak or inexistent i.e., in rural areas and other remote regions. The ability to store renewable energy in different time scales, either in the form of electricity or other energy carriers such as thermal energy and hydrogen, storage technology enables a faster energy transition fostering the electrification of the economy and the decarbonization of other economic sectors.

The participation of ESS in electricity markets has the potential of reducing price fluctuations by providing peak 'shaving' in periods of higher power demand and by 'shifting' energy from periods of energy surplus and with lower demands to deficit periods, of higher prices. The provision of peak capacity, balancing, and non-frequency ancillary services position ESS as the alternative to fossil-fueled power plants on electricity system stabilization. The same applies with regards to resilience and reliability of the energy system by providing adequate restoration capabilities in case of outages, taking advantage of the large pool of different energy and power capacities and response times ranges available within the storage technologies.

Behind the meter, energy storage starts to play an increasingly valued role, supporting the optimization of energy management of active consumers and prosumers by maximizing self-consumption of local produced renewable energy and facilitating the integration of higher power processes. An example of the latest is the integration of electric vehicles power charging. In this case, large investments on the local infrastructure upgrade can be replaced by batteries, which provide the flexibility for scheduling the charging times to more compensatory periods benefiting from energy costs reduction due to shifting renewable energy surplus or storage grid electricity at lower prices.

The generic development level of each storage technology, and the performance level of the technical parameters of each solution, defines its usefulness and readiness in the power management system. In Figure 27 the distribution of adequacy of each main group of storage systems is shown, as well as some particular technologies, parametrized by the typical figures-of-merit in the energy storage state of the art assessment: the pair discharge duration / power capacity. These two parameters are used to identify the main operational application domains of each kind of technology: reserve and response services on the energy supply, support to the distribution and transmission infrastructure and bulk power management.

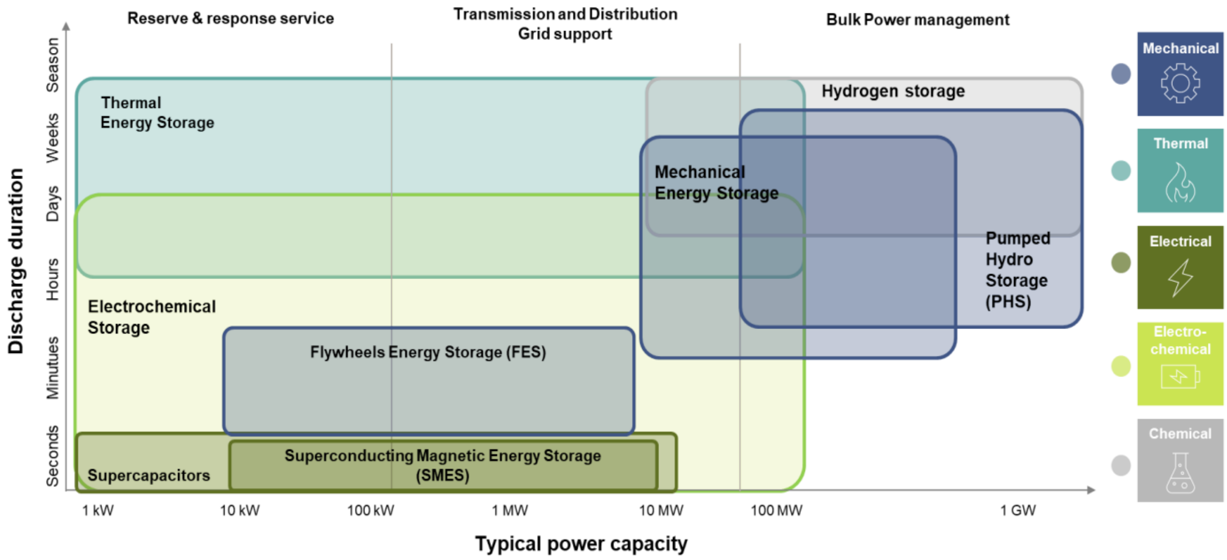

FIGURE 27: MAIN STORAGE TECHNOLOGIES GROUPS DISTRIBUTION TO SUPPORT THE SYSTEM BY DISCHARGE TIME AND SYSTEM POWER RATING. THIS FIGURE IS TAKEN FROM [119]

An extended review of key parameters that constrain technically the application fields of each technology can be seen in Table 12 [120], [121]. The ESS technical parameters selected for the analysis help to characterize the technologies in accordance with their potential applications:

- Efficiency
  - Round-trip efficiency
  - Conversion efficiency (for storage of other energy carriers then electricity)
- Capacity

- Power installed capacity
- Energy capacity
- Dispatchability (charge/discharge behaviour)
  - Storage duration at full power
  - Response time
- Lifetime and maximum number of cycles
- Qualitative maturity

		Gravitational/ Mechanical			Electrochemical						Chemical	Thermal			Electrical	
		PHES	CAES	Low-speed flywheel	Lead-Acid (Pb-A) batteries	Sodium-Beta (Na-β) batteries	Lithium-Ion batteries	Metal-Air batteries	Nickel-Based batteries	Flow batteries (VRFB)	Power to Hydrogen	Sensible Heat Storage (HS)	Latent HS	Thermochemical HS	Supercapacitor	Superconducting magnetic (SMES)
Efficiency	Round-trip efficiency (%)	70 - 85	> 70	85 - 95	75 - 85	< 92	85 - 89	60 - 80	60-70	68-80	20 - 40	>98-99	> 90	40-60	90 - 95	90 - 95
	Conversion efficiency (%)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	54 - 83 kWh/kg H2	-	-	-	n.a.	n.a.
Capacity	Power installed capacity	10 MW - 3 GW	10-300 MW	1 - 20 MW	< 40 MW, (typ. 1 MW)	20-250 kW	< 500 MW	Some MW	< 40 MW	< 200 MW	1 kW -1 GW	75-330 MW	3.5 kW	500 W	> 300 kW	> 40 MW
	Energy capacity	0,5 - 100 GWh	100 MWh - 10 GWh	5 kWh - 5 MWh	< 10 MWh	< 1 MWh	< 1000 MWh	Some MWh	Some MWh	10kWh - 800 MWh	kWh - several GWh	350-4000 MWh	7,66 kWh	1 Wh		
Storage charge/discharge behavior	Storage duration at full power	min - days	hours-days	sec - min	1 to 6 hours	< 4 to 5 hours	5 min to 6 hours	hours	min-hours	10-12 hours	hours - weeks	hours-months	hours-weeks	hours-days	sec - min	msec – min
	Response time	sec – min	min	sec	msec	msec	msec	msec	msec	msec - sec	sec - min	<1 minutes	<1 minute	Minutes	msec	5 msec
Lifetime	Lifetime (years)	50 - 100	> 30	> 20	8 - 20	< 10	10-20	n.a.	10 - 25	10-25	5 - 30	-	-	-	> 20	20 - 30
	Number of cycles	20k-100k	< 1000	100k-10M	250-2k	< 1.5k	1.5k – 3.5k	10-100	1k -5k	>10k	n.a.	10k	3k -3.5k	< 100	100k-100M	100k
Maturity		mature	mature	Comme-rcial	Comme-rcial	R&D	Comme-rcial	R&D	Comme-rcial	Comme-rcial	Comme-rcial	mature	R&D	R&D	Comme-rcial	mature

Table 12: Energy storage technologies' key features [120], [121]

The existence of diverse technological solutions covering a wide spectrum of modular storage capacities and response times, categorized as mature or already available in the market should not be interpreted directly as a lack of technical barriers. The integration of novel ESS in the power system requires necessarily the test of new configurations in conjunction with established technologies, which can present significant technical challenges. Features such as the lifetime, reliability issues and OPEX can hamper the growth in acceptance and deployment of the technologies [122], even when the proof of concept has been commonly accepted. The TRL's scale quantifies the stage of development of a new technology focusing on its technical development and ultimately its readiness for commercialization; however, when considering the technical maturity of ESS technologies, it does not incept the maturity of their application in combination within the energy system itself. This fact gains even more relevance when applications use several types of energy generation technologies and storage, such as the hybrid energy storage systems (HESS). While individually, each ESS of a hybrid system is a mature/proven technology i.e. with high

TRL, there may still be considerable uncertainty associated with their use in combination in the energy systems. Therefore, interoperability and control issues, as so as the lifetime expectance and reliability of the combined solution under specific regimes of usage, may represent a risk for investment not only to system planners and operators, but also for the business developers. This intrinsic condition of the innovation process, here particularly focusing on the combination of several technical complementary solutions illustrates by itself the potential for finding unforeseen technical barriers, which in turn highlights the relevance of demonstrator projects to mitigate the risk.

3.1.1.1 Ancillary and grid management services

Energy-storage technologies can provide many different services to the energy system depending on each type of technology capacity to respond to the technical requirement of the mechanisms, the energy and discharge capacity rates as well as the rate of self-discharge. Pumped hydro storage is historically the most adopted technology for participating in energy markets, while newer technologies such as battery storage are just starting. The fast-paced deployment of these opens opportunities to further develop and adapt the services and functionalities responding to the growing need of flexibility in the energy system. The benefits that storage brings to power system operation should be commonly recognized and remunerated through market-oriented mechanisms. However, the entry of storage technologies in the markets is limited by the internal rules, regulatory and markets organization, of each country in the participation of the several services.

The next section identifies and categorizes the energy storage services and the limiting features that defines the adequacy of each type of ESS technology for each of them and presents an overview on the recently identified and proposed new services to energy storage.

3.1.1.2 Technical adequacy

Ancillary and grid management services are a relevant potential revenue stream for energy storage deployment. Due to the high level of controllability, modularity, and diverse response times among the available energy storage solutions, especially when combined in hybrid systems, they can offer a wide range of actuation covering a large spectrum of functionalities and services to the grid operators and to the end-users. It is recognized by the regulators and network operators that the increasing penetration of highly variable renewable generation technologies requires flexibility in the system such as the provision of ancillary services, and other different time-scale support services and functions. ESS can then provide similar services to the power system as other traditional flexibility resources and are usually treated equally in a technology-neutral approach, which may constitute a barrier to entry if the technical characteristics of storage are not considered when designing the products to be procured.

Pumped hydro Energy storage has traditionally been the most adopted technology for balancing and non-frequency ancillary services, but more recently batteries have been gaining significant momentum with the advantage of their modularity and distributed geographical application and the capacity to be used in the provision of different functionalities opening the possibility of stacking different revenue streams. Hence, it is important to clearly identify and categorize the application of such an already vast portfolio of storage technologies.

The European Association for Storage of Energy [126], provides an updated list and description of the most common and suitable services for energy storage systems. Table 13 summarizes them according to market main category and minimum key energy storage feature as follows:

TABLE 13: ENERGY STORAGE GRID MANAGEMENT SERVICES AND FUNCTIONALITIES PER APPLICATION FUNCTIONAL GROUP [126].

Services group	Minimum key feature	Services/functionalities
Generation Support Services and Bulk Storage Services	storage duration of minutes to several hours	- Storage Services for RES support - Arbitrage - Capacity firming - System electricity supply capacity - RES curtailment minimization - Support to conventional generation - Seasonal arbitrage
Services to support transmission infrastructure	ramp-up within milliseconds or minutes	- Transmission support - Transmission investment deferral - Angular Stability
Services to support distribution infrastructure	storage duration of one or more hours	- Distribution grid upgrade deferral - Dynamic local voltage control - Reactive power compensation - Contingency grid support - Intentional islanding - Cross Sectorial Storage
Services to support distribution infrastructure	storage duration of one or more hours	- Distribution grid upgrade deferral - Dynamic local voltage control - Reactive power compensation - Contingency grid support - Intentional islanding - Cross Sectorial Storage
Ancillary services	No minimum capacity, response and storage times requirements	- Frequency containment reserve – FCR - Automatic frequency restoration reserve - aFRR - Manual Frequency restoration reserve - mFRR - Replacement reserve – RR - Load following - Frequency stability of weak grids - Blac start - Voltage support
Services to support behind the meter customer energy management	power installed capacity starting from 100 kW	- End-user peak-shaving - Maximizing self-production and self-consumption of electricity - Continuity of Supply - Time-of-use energy cost management - Limitation of upstream disturbances

	- Requirements in power quality - Compensation of reactive power - EV integration

Among the available energy storage technologies, a mapping of the potential applications and services of the energy storage technologies foreseen in the HESS demonstrators of the i-Stentore project is presented, in accordance with the technical features presented in the next table, organized by high level functional groups:

- Energy supply support and bulk storage services (see Table 14)
- Services to support transmission and distribution infrastructure (see Table 15)
- Ancillary services (see Table 16)
- Services to Support Behind the Meter Customer Energy Management

	Gravitational/ Mechanical			Electrochemical						Chemical	Thermal			Electrical	
	PHES	CAES	Low-speed flywheel	Lead-Acid (Pb-A) batteries	Sodium-Beta (Na-β) batteries	Lithium-Ion batteries	Metal-Air batteries	Nickel-Based batteries	Flow batteries	Hydrogen	Sensible Heat Storage (HS)	Latent HS	Thermochemical HS	Supercapacitor	Superconducting magnetic (SMES)
Storage Services for RES Support	●	●		●	●	●	●	●	●	●	●		●		
Arbitrage	●	●		●	●	●	●	●	●		●		●		
Capacity Firming	●	●		●	●	●	●	●	●	●	●		●		
System Electricity Supply Capacity	●	●		●	●	●	●	●	●	●	●		●		
RES Curtailment Minimisation	●	●		●	●	●	●	●	●	●	●		●		
Support to Conventional Generation	●	●		●	●	●	●	●	●		●		●		
Seasonal Arbitrage	●	●								●			●		

TABLE 14: ENERGY SUPPLY SUPPORT AND BULK STORAGE SERVICES [120], [121]

		Gravitational/ Mechanical			Electrochemical						Chemical	Thermal			Electrical	
		PHES	CAES	Low-speed flywheel	Lead-Acid (Pb-A) batteries	Sodium-Beta (Na-β) batteries	Lithium-Ion batteries	Metal-Air batteries	Nickel-Based batteries	Flow batteries	Power to Hydrogen	Sensible Heat Storage (HS)	Latent HS	Thermochemical HS	Supercapacitor	Superconducting magnetic (SMES)
Transmission	Transmission Investment Deferral	●	●		●	●	●	●	●	●						
	Angular Stability			●	●	●	●	●	●						●	
	Transmission Support	●	●	●	●	●	●	●	●	●						
Distribution	Distribution Grid Upgrade Deferral				●	●	●	●	●	●						
	Dynamic Local Voltage Control	●			●	●	●	●	●	●						
	Reactive Power Compensation	●			●	●	●	●	●	●						
	Contingency Grid Support	●		●	●	●	●	●	●	●					●	
	Intentional Islanding				●	●	●	●	●	●						
	Cross Sectoral Storage										●	●		●		

TABLE 15: SERVICES TO TRANSMISSION AND DISTRIBUTION [120], [121]

		Gravitational/ Mechanical			Electrochemical						Chemical	Thermal			Electrical	
		PHES	CAES	Low-speed flywheel	Lead-Acid (Pb-A) batteries	Sodium-Beta (Na-β) batteries	Lithium-Ion batteries	Metal-Air batteries	Nickel-Based batteries	Flow batteries	Power to Hydrogen	Sensible Heat Storage (HS)	Latent HS	Thermochemical HS	Supercapacitor	Superconducting magnetic (SMES)
Ancillary Services	Frequency Containment Reserve (FCR)	●	●	●	●	●	●	●	●	●	●	●				
	Automatic Frequency Restoration Reserve (aFRR)	●	●		●	●	●	●	●	●	●					
	Manual Frequency Restoration Reserve (mFRR)	●	●		●	●	●	●	●	●	●					
	Replacement Reserve (RR)	●	●		●	●	●	●	●	●	●					
	Load Following	●	●	●	●	●	●	●	●	●	●	●				●
	Frequency Stability of Weak Grids			●	●	●	●	●	●	●						●
	Black Start	●	●		●	●	●	●	●	●	●					
	Voltage Support	●	●		●	●	●	●	●	●						

TABLE 16: ANCILLARY SERVICES [120], [121]

Services to Support Behind the Meter Customer Energy Management

Behind-the-meter (BTM) storage is particularly interesting for households and industries ultimately to capacitate them as active players participating in the electricity markets as consumers and flexibility providers. EU directives, such as, REDII (Directive (EU) 2018/2001) [127] and the Energy Market Directive (Directive (EU) 2019/944) [125] have been promoting an increasing growth of the distributed generation from RES by establishing common rules for internal markets of electricity, fomenting the aggregation [125] of end-users' decentralized generation capacities, including collective systems of energy communities, where behind-the-meter energy storage can increase the benefits of demand-side flexibility and valorize the energy supply services to the grid distribution operation and transmission in a non-discriminatory manner. In this context, storage energy systems are especially relevant to maximize self-consumption of self-produced renewable energy, the end-users can increase their saving by storing the excess renewable energy when the load is low and use it later when the load is high (renewable time shift). BTM storage also offers the opportunity to flexibly adapt the consumption to price signals; by managing the time-of-use (TOU), user can benefit by storing during the off-peak and then consuming that energy during the peak hours. Together with end-user peak shaving, both the energy and network power demand charges can be significantly reduced. Furthermore, decentralized BTM storage energy systems can provide power quality and reliability of energy supply for end-users and also to the local infrastructure, for example in case of outages in the grid, or if a specific high-level power-quality requirement is required in an industrial application.

Among the considered storage technologies in this project, behind the meter applications have been led by lead-acid and Li-ion BESS [128] which technically are suitable to cover the renewable time shift, TOU management and peak-shaving. Nonetheless, [129] the adoption hydrogen is becoming more attractive as the prices of the eletrolysers and fuel cells tend to decrease, but costs associated to maintenance with smaller sizes application are still hampering their adoption in a large scale. Thermal energy storage, also shows many advantages as BTM technology, improving the overall efficiency of heating and cooling renewable systems, such as solar thermal, geothermal, and air-to-air heat exchange systems, such as heat pumps. Furthermore, coupling thermal storage with electricity resources, e.g. as photovoltaic, can potentially contribute to the reduction of energy costs of climatization and domestic hot water heating by shifting renewable electricity surplus, or when the electricity tariff is lower.

3.2 ENERGY MARKETS' DESIGN BARRIERS

An important technical source of barriers for the ESS deployment in the network are the markets design issues and the discriminatory bias of network operators when planning the network. Smaller storage assets adoption is still not fully considered as reliable and secure, limiting the monetization of the potential services. Albeit during the last decade advances in establishing flexibility base markets in most of EU member states have been ongoing, specific market design parameters still act as participation barriers to energy storage technologies, in some countries, such as minimum bid sizes, price caps, limitations on the payments and procurement contracts design. Also, barriers to entry are usually related with technical requirements, which is the case of real-time data transmission, required to provide balancing services, that most of times is not available or is disproportionally costly for smaller storage applications hindering their qualification for participating in markets that require high granularity data (e.g. Frequency Containment Reserve).

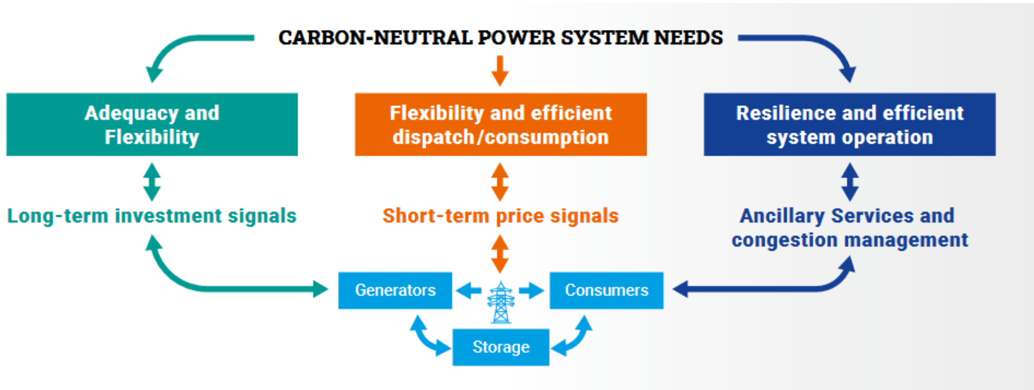

FIGURE 28: ENERGY MARKETS ORGANIZED BY DIFFERENT TIME SCALE SERVICES SUPPORTED BY ENERGY STORAGE TECHNOLOGIES [130].

Energy storage can provide a range of services such as black start, voltage regulation, reactive power, and congestion management. New market designs need to be further developed ensuring that these services are procured from low-carbon sources to support the grid.

According to the EU electricity market design directive [125] new adaptive markets should be implemented creating an attractive environment for investment in a more flexible system by supporting the operation of storage energy solutions and demand side response that can complement the variable and distributed renewable energy production ensuring in this way a stable, secure, and reliable common energy system (Figure 28). An organized competitive market for storage operators' participation with single technology applications or combined hybrid systems is encouraged, either via transactions in organized exchanges or over the counter directly or via aggregation. Aggregation has the potential to unlock the operation of virtual power plants (VPPs), a key concept in making energy storage economics more attractive. The combination of heterogenous distributed energy resources and different availability of storage assets operated through the same orchestration system can offer fine-tuned flexibility to the power system, making it possible to access value stacking opportunities for which conventional centralized and single technology power plants are not eligible.

In most EU Member States markets design has introduced flexibility services in the short-term day-ahead, intraday and balancing markets to ensure an efficient dispatch of generation and consumption, optimising an integrated energy system; nevertheless, several services are still not remunerated or are not attractive, e.g., non-frequency ancillary services such as voltage control and black start [131]. Capacity mechanisms are also appropriate for the participation of diverse energy storage systems technically adequate of ensuring the availability of enough firm capacity, complying with Clean Energy Package carbon-neutrality imposed emission limits (550 g/kWh) [124]. Capacity markets should be designed based on capacity payments or with quantity mechanisms yet are still currently limited by the lack of adequate long-term financial market instruments alongside short-term dispatch mechanisms, which are indispensable to ensure the market liquidity. Therefore, procurement contracts for services must evolve towards higher diversity allowing the development of more competitive models of value stacking for storage operators. Long-term services can benefit from the participation of energy storage in other markets while the availability of capacity is not activated (see in Figure 29 the different time-scales of the ancillary services). Therefore, an adequate instrument to foster storage developers' investments is mid- and long- term forward contracts with the system operators, alongside with proper regulated of multi-nature services' stacking increasing the revenues streams. In turn, given a future pool of short-term flexibility services, the markets should evolve to operations closer to real-time, adopting shorter price signals, in opposition to present wholesale markets, working in day-ahead and intraday markets to ensure an efficient dispatch of generation and consumption, optimising an integrated energy system.

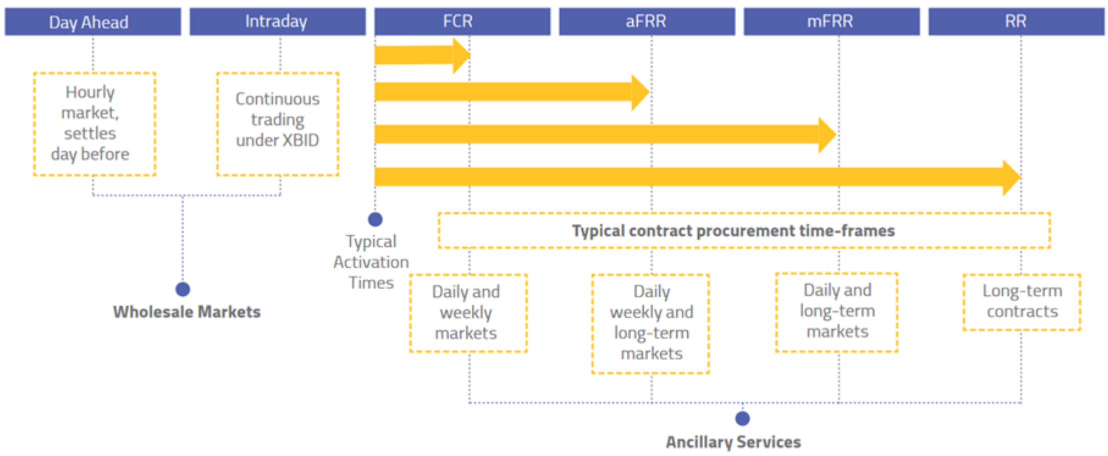

FIGURE 29: TYPICAL ANCILLARY SERVICE TIME-FRAMES [132]

In order to overcome and synchronize EU member states' energy markets rules and formats, since 2018, ENTSO-E (European association for the cooperation of transmission system operators) has been promoting cooperation projects among the EU region to test and integrate new balancing markets rules and standards and ultimately transform the balancing energy markets from national to a pan-European matter, following the recommendations of the Electricity Balancing Guideline (EBGL) [133] by introducing standardised products ensuring requirements that are in line with the technology neutrality principles of the Electricity Market Directive [125] and Regulation [124].

ENTSO-E created the following platforms towards harmonized procurement methods and technical requirements to the participation in the various balancing market processes (see Figure 30Figure 30), which detailed codes description can be found in [134]:

- IGCC - International Grid Control Cooperation for imbalance netting process;
- PICASSO - Platform for International Coordination of Automated Frequency Restoration and Stable System Operation (aFRR);
- MARI - Manually Activated Reserves Initiative for (mFRR);

- TERRE - Trans-European Restoration Reserves Exchange (RR).

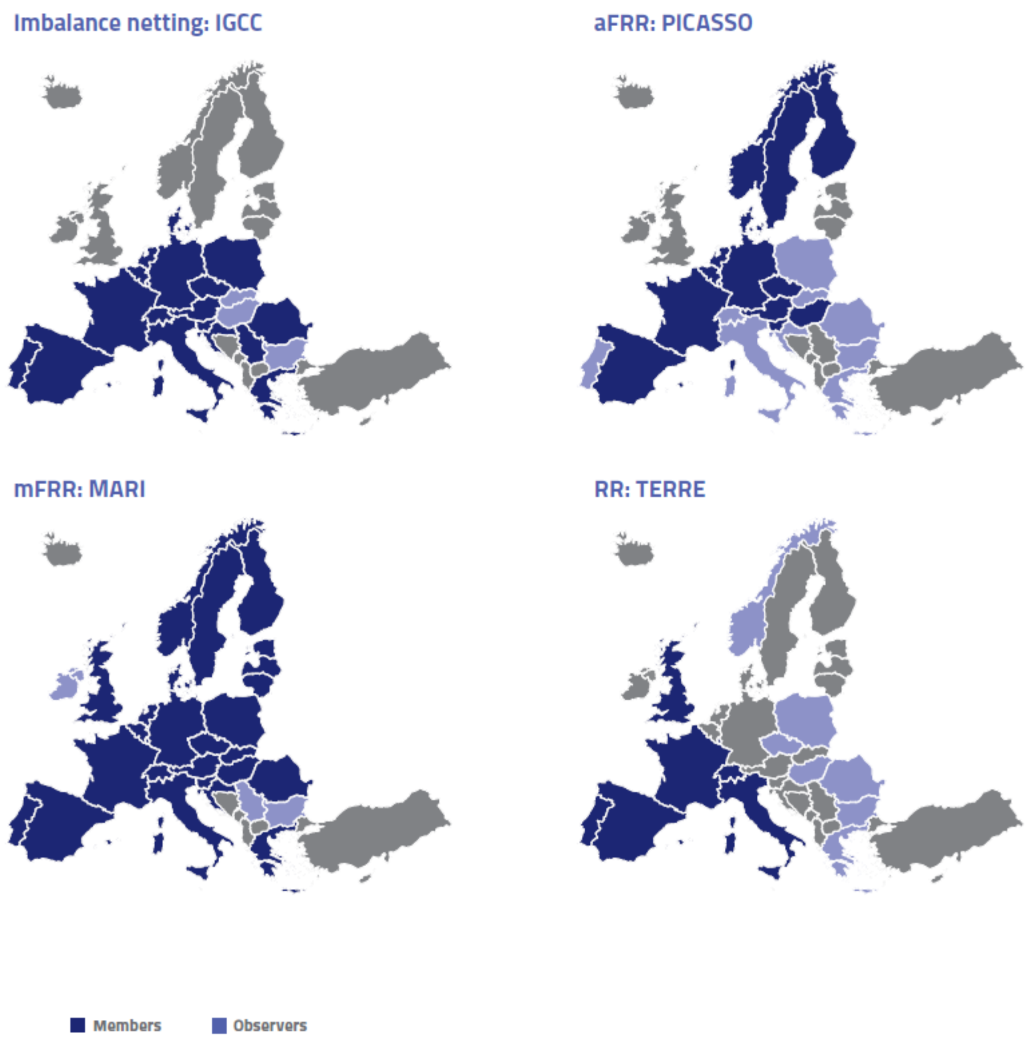

FIGURE 30: EUROPEAN BALANCING IMPLEMENTATION PROJECTS (BLUE) AND OTHER TSO MEMBERS (LIGHT BLUE) AS OBSERVERS [132]

The European Balance market projects expansion and integration will create more efficient procurement, more flexible and therefore reliable reserve power provision, enabling an energy system in which distributed renewable sources are the backbone of the energy supply enabling new actors in services provisioning from the grid-level down to the end-consumers level, who will play a more active role. The Integration of European balancing markets is estimated to generate additionally more than 400 million euros per year [135]. Figure 31, shows the projection for the evolution of grid-scale energy storage markets in energy volume, GWh, for this decade base on the adoption trends of EBGL [133] by the top 10 countries in European Union, and in this case due to it relevancy, including the UK.

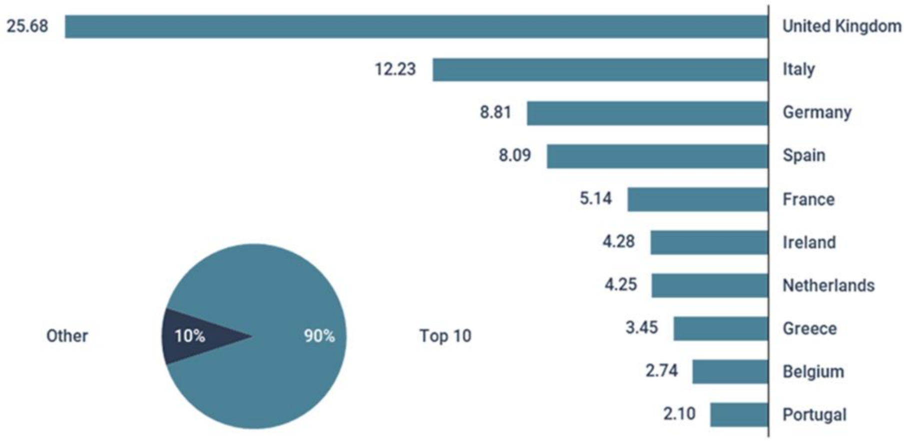

FIGURE 31: TOP 10 EUROPEAN GRID-SCALE ENERGY STORAGE MARKETS, CAPACITY 2022-2031 GWH [136]

However, even with a certain level of standardization, there is still a long way to go as some of the participating countries have requested derogations, delaying the development of these markets. For example, inside EU cooperation platforms for FCR, aFRR, mFRR and RR the low bid minimum size was set to 1 MW, allowing the pooling of generation and energy storage and other demand resources. However, aggregation is still not allowed in some energy markets. In other cases, demand-side resources that can technically participate in TSO markets are blocked by required bid sizes higher than 1 MW, up to 5 MW or even 10 MW [137]. This is a perfect example of a barrier to entry that should lead to the revision of minimum bid sizes even below 1 MW, complying with the non-discriminatory access of storage and other distributed demand-respond processes enabling the direct participation of independent aggregators as Balance Service Providers (BSP) in the markets.

3.2.1 Status in the Demo Countries

The next section aims to give an overview of the current state of energy balancing markets in the project demonstrator countries, indicating potential barriers to entry and participation of energy storage technologies. The information was collected from ENTSO-E annual Market reports [138]–[141] and [142].

3.2.1.1 Greece

The Greek balancing market includes an integrated scheduling process for FCR, aFRR and mFRR through a market-based mechanism of central dispatch. In Table 17 some key markets conditions are summarized.

The TSO, IPTO, announced the market opening to demand-side resources, storage, and distributed energy resources. Demand side flexibility market has a potential size estimated in around 800 MW. The size of balancing reserves, which are mostly procured from generators, are: for FCR, of around ±1000 MW; for aFRR, around 3900 MW upwards and downwards, and 4700 MW (upwards and downwards) for the mFRR market.

In terms of data communication, the TSO requires both real-time monitoring and posterior verifications. Data updates on generation, demand and interconnection loads is provided monthly.

ACCESS TO ANCILLARY SERVICES		
FCR	aFRR	mFRR and RR
procured through a market-based mechanism only open to generation assets with a minimum bid size of 1 MW.	procured through a market-based mechanism only open to generation assets with a minimum bid size of 1 MW.	mFRR is procured through daily and intra-daily auctions open only to generators with a minimum bid size of 1 MW. RR not supplied.
capacity and energy are procured day-ahead auctions.	both reserve and balancing energy are procured through daily and intraday auctions	both reserve and balancing energy are procured through daily and intraday auctions
balancing energy for FCR is not settled	Asymmetrical bids are allowed. Balancing energy for is compensated at a marginal price with a resolution of 15 minutes. FAT[1] is 5 to 7.5 min.	Asymmetrical bids are allowed. Balancing energy is compensated at a marginal price with a resolution of 15 minutes. Fat is 5 to 10 min.
EU FCR Cooperation Member.	PICASSO platform member. Asked for a derogation for the connection until July 2024.	MARI platform member. Asked for a derogation for the connection until July 2024.

TABLE 17: BALANCE SERVICES STATUS FACTS SHEET IN GREECE.

3.2.1.2 Italy

Italian TSO, Terna, implemented in 2019 a pilot project for a tertiary electric reserve to balance the power grid, UVAM (Virtual Mixed Aggregated Unit) [143], opening the markets of aFRR, mFRR and RR, progressively in different time phases, for demand side flexibility providers participation. The pilot was designed to reach the 1000 MW of procurement for distributed flexibility. The access of demand-side resources participating in the ancillary services market has been growing since then, mainly for mFRR and RR, but is still far from the initial expected volumes. In Table 18 are summarized some key markets conditions. High energy prices have been causing substantial losses to the mFRR participants due to the static cap prices originally defined that are currently below energy prices. This is hampering the stabilization of a market for ancillary services where generation and storage and other demand response assets can compete. The losses have been forcing some UVAM operators to leave the market.

In the case of the aFRR product, the remuneration consists of energy-only payments without applying a strike price. These remunerations are often very low and not sufficient for recovery

[1] FAT - Full activation time (FAT)

of the entrance investments. Nevertheless, in 2022, there was 1104 MW of qualified capacity in UVAM, with 3400 MWh of demand side flexibility activated in the first 5 months of that year [144].

Concerning Frequency Containment Reserve, the service is not procured through a market-based mechanism. It is supported by generation units and co-generators with a capacity starting at 10 MVA. Also, Italy is not part of the EU FCR Cooperation.

A new fast reserve product targeting large scale batteries (> 1MW) was implemented as a pilot project. Still in a development phase, it has been hindered particularly due to the lack of clear definitions of the aggregation role, demand-side resources and flexibility services.

ACCESS TO ANCILLARY SERVICES		
FFR	aFRR	mFRR and RR
In 2020 was tested a pilot for fast reserve open to stand-alone and behind-the-meter production units, demand response assets and storage devices both stand-alone and behind-the-meter (200MW)	procured through an energy-only market-based mechanism with a minimum bid size of 1 MW. Is open generation and to demand-side resources.	mFRR and RR are available is procured through daily and intra-daily auctions open to generators and demand-side resources (UVAM project) with a minimum bid size of 1 MW. RR not supplied.
Aggregation was allowed within the same bidding zone with a minimum bid size of 5 MW. Assets already qualified for the capacity market were restricted to participate in this reserve to avoid double remuneration.	Aggregation is allowed. remuneration consists only of energy payments	Aggregation is allowed. TSO procures around of 1 GW mFRR and RR through annual tenders (70% of the total capacity) Participants can offer their services through monthly auctions with pay-as-bid with price cap of 30 k€/MW. TSO is the single buyer (price cap of 440€/kWh)
Activation times of 1 second.	Asymmetrical bids are allowed.	Asymmetrical bids are allowed.
-	Connection to PICASSO platform foreseen to July 2023.	TERRE platform member. Connection to MARI platform foreseen to July 2023.

TABLE 18: BALANCE SERVICES STATUS FACTS SHEET IN ITALY.

3.2.1.3 Luxembourg (Amprion LFC block)

Luxembourg belongs of the Load-Frequency Control Area of Amprion (LFC), one of the four German TSOs, as such, the Luxembourgish TSO, Creos, adopts all balancing regulations implemented by Amprion. As part of German system, Luxembourg has access to one of the biggest markets in Europe for capacity for ancillary services procurement. Nevertheless, the market remains dominated by conventional generation assets; only 2% of the total procured capacity comes from DSF assets. Hydro power plants and traditional generation from gas are the main technologies procured for ancillary services. Energy storage systems, mainly front-of-the-meter batteries but also from EVs, are used almost exclusively for FCR.

Within the LFC area, the several operators form balancing pools, managed by a balance responsible party. TSOs hold a share of the overall FCR equivalent to the electricity generation and withdrawal in the synchronous area. Since December 2019, Germany has applied a dynamic dimensioning approach for aFRR and mFRR, to adapt the demands to the relevant situation on shorter notice. In Table 19 are summarized some key market conditions.

Despite the fact that FCR, aFRR and mFRR are open through market-based mechanisms to storage and other demand-side flexibility assets operators, technical and permitting barriers still hamper their entry and participation in these markets. The most relevant is linked to the limitation for aggregation only within the same balancing area, and the requirement of electing a certified balance responsible party recognized by the consumer's supplier, which imposes a considerable bureaucracy on markets participation. Furthermore, delays in the digital transition, have been a limiting factor for the participation of innovative technologies, especially for active consumers. TSOs require real-time metering data transmission through traditional leased lines, although small assets (< 100 kW) are now allowed to use the regular internet connection significantly reducing the financial burden for the operators.

ACCESS TO ANCILLARY SERVICES		
FCR	aFRR	mFRR and RR
Procured through daily auctions in four-hour blocks from bids with a minimum size of 1 MW, open to demand response and generation assets.	Procured through day-ahead capacity and energy market-based mechanisms with a minimum bid size of 1 MW. Is open generation and to demand-side resources.	Procured through day-ahead capacity and energy market-based mechanisms with a minimum bid size of 1 MW. Is open generation and to demand-side resources. No RR product used
Assets pools are allowed to offer asymmetrical FCR providing that are able to offer symmetrical FCR.	Aggregation of demand and generation in the same pool is allowed	Aggregation of demand and generation in the same pool is allowed
BSPs obtain a price for capacity reserve (including costs for energy)	Asymmetrical bids are allowed. Balancing energy is procured for 15 min. blocks and the full activation time is 5 min	Asymmetrical bids are allowed. Full activation time is 12.5 min.
-	Remuneration through both availability and energy payments	Remuneration through both availability and energy payments
FCR cooperation member	PICASSO platform member	MARI platform member

TABLE 19: BALANCE SERVICES STATUS FACTS SHEET IN AMPRION/CREOS LFC BLOCK.

Co-funded by the European Union

3.2.1.4 Portugal

In Portugal, the regulatory constraints remain the main barrier for the participation of demand-side resources in ancillary services markets.

The aggregation was legally defined in 2022 [145], yet practical improvements and adaptations of the system have to be further implemented in order to enable flexibility providers accessing the different ancillary services markets.

FCR is not procured through a market mechanism. The produced power is supplied by mandatory provision for generators defined by the TSO, REN. From the energy balancing services, mFRR is the only one allowing the demand-side response but just by consumption, in this case for industrial assets above 1 MW. The qualification requirements are mostly designed to address generation features. REN, launched in 2019 a pilot project to explore flexibility operational products in mFRR, concluding that the major barrier for distributed demand response participation are the data monitoring and communication required.

The secondary reserve is defined asymmetrically with a ratio of 2 between upward and downward regulation, which can constitute a barrier for demand technologies, such as energy storage systems, that while able to participate in aggregation will not be able to provide symmetrical load variations.

The Portuguese market is presently composed of essentially contracted conventional generators and PHES for aFRR, 180 MW, upward, and 90 MW, downward. mFRR and RR are procured considering the sum of the largest available generation asset (400 MW) plus 2% of the forecasted demand (capped to 200 MW) plus 10% of wind forecasted generation (capped to 540 MW). The Manual Frequency Restoration Reserve accounts for around 30 MW of industrial loads for contracted for consumption.

aFRR	mFRR and RR
procured through an energy-only market-based mechanism with a minimum bid size of 1 MW. Is only open to generation, mostly from thermal and hydro power plants.	mFRR and RR are available is procured through daily auctions open to generators and demand-side (only for industrial consumers) with a minimum bid size of 1 MW.
Aggregation is not allowed	Aggregation is not allowed.
The reserve is asymmetrical with a ratio of two between upward and downward regulation.	Remuneration of mFRR auctions is based on activation and are only-energy. Availability payments is not foreseen.
Connection to PICASSO platform foreseen to mid 2024.	MARI platform member. Asked for a derogation for the connection.

TABLE 20: BALANCE SERVICES STATUS FACTS SHEET IN PORTUGAL.

Co-funded by the European Union

3.2.1.5 Slovenia

Since 2019, a new regulatory framework opened the possibility of demand-side resources participation in ancillary services markets. Aggregation of energy storage assets, industrial loads and distributed generation is allowed provided that the conditions for participation of demand and generation are equal, thus fostering more diverse and dynamic markets. Equal payments are granted to generation and demand-side resources when in the market.

The technical requirements for qualification of demand-response assets have been proven adequate. Also, a marginal price logic is applied for FCR, through the FCR Cooperation, and a pay-as-bid logic for aFRR and mFRR. In Table 21 some key markets conditions are summarized.

As a relevant measure to stimulate the demand response participants and storage operators, ELES, the Slovenian TSO, has implemented specific exemptions for aggregators, relaxing usually mandatory compensations to the suppliers in case of energy unbalances as result of providing demand response.

Concerning data monitoring, the TSO established accuracy requirements adjusted to the size of the assets, organized in three classes (up to 1 MW). Nonetheless, the TSO requires real-time telemetry for providing balancing services which can represent a barrier for smaller assets considering the relatively high costs of investment of the monitoring and transmissions systems' integration.

The Slovenian market design efforts attracted an expressive participation of demand-side resources in aFRR and mFRR markets. aFRR accounts for significant shares of demand-side assets procuring these types of reserve. In terms of activated energy, 36% for aFRR and 25% for mFRR, were supported by flexibility suppliers, mostly batteries, industrial consumers and small-scale generators [142].

ACCESS TO ANCILLARY SERVICES		
FCR	aFRR	mFRR and RR
Procured through daily auctions in four-hour blocks from bids with a minimum size of 1 MW, open to demand response and generation.	Procured through a market-based mechanism, in through monthly and daily auctions, open to demand response and generation assets with a minimum bid size of 1 MW.	Procured through a market-based mechanism, in through daily auctions, open to demand response and generation assets with a minimum bid size of 1 MW. (multi-annual contract for upward mFRR that expires at the end of 2023)
Balancing energy is not procured through a market-based mechanism. Balance providers must meet the amount of energy corresponding to a 15-minute activation of the maximum amount of the provided balancing capacity.	Both reserve and balancing energy are procured through daily auctions.	Both reserve and balancing energy are procured through daily auctions.

-	Aggregation of demand and generation in the same pool is allowed.	Aggregation of demand and generation in the same pool is allowed.
-	Asymmetrical bids are allowed.	Asymmetrical bids are allowed.
EU FCR Cooperation Member.	PICASSO platform member. Asked for a derogation for the connection until July 2024.	MARI platform connection planned for Q3 2023

TABLE 21: BALANCE SERVICES STATUS FACTS SHEET IN SLOVENIA.

3.2.1.6 Spain

In Spain not all ancillary services are procured through market-based mechanisms. Despite recent regulation adaptations, demand-side flexibility and energy storage-based services are equated to generation with regards to the participation in balance markets.

A minimum portfolio size of 200 MW for aggregated units is necessary for procurement in the aFRR market. The major barrier for demand resources, including energy storage, is the absence of procurement of capacity for mFRR and RR reserves that limits the participation in energy balancing, for which the profitability of energy-only payments is still very low, thus hindering the business models of developers. Therefore, the spread between the balancing market price and the day-ahead price resulting from compensation of the balance responsible parties is particularly limited, around 10-40 €/MWh, which is not sustainable for the business model of flexibility demand providers.

The regulation on the role of aggregators must evolve towards an effective participation of smaller assets. In October of 2022 a new fast frequency reserve for consumption units of minimum bid size of 1 MW was implemented, however this mechanism excludes independent aggregators; the participation is exclusive to contracted balance responsible parties. In Table 17 some key markets conditions are summarized.

In Spain ancillary services are mainly provided by conventional generators, renewables, and hydro power plants. The procurement of reserves for aFRR is around 800 MW and none is secured by energy storage.

ACCESS TO ANCILLARY SERVICES		
FCR	aFRR	mFRR and RR
FCR is a mandatory service for generators and not remunerated.	Procured through a market-based mechanism, in through monthly and daily auctions, open to generation and demand response assets with a minimum bid size of 1 MW. The resources must belong to the same regulated zone with a minimum portfolio size of 200 MW	Procured through a market-based mechanism, in through daily auctions, open to demand response and generation assets with a minimum bid size of 1 MW.

Co-funded by
the European Union

Balancing energy is not procured through a market-based mechanism.	Both reserve and balancing energy are procured through daily auctions.	Only balancing energy reserves are procured. Remuneration of mFRR auctions is based on activation and are only-energy
-	Aggregation of demand and generation is allowed for recognized balance responsible parties, but in different pools. (independent aggregators are excluded)	Aggregation of demand and generation is allowed for recognized balance responsible parties, but in different pools.
-	Asymmetrical bids are allowed.	Asymmetrical bids are allowed, and balancing energy is compensated at a marginal price with a resolution of 15 minutes. Activation times of mFRR is 15 min. and 30 min. for RR
EU FCR Cooperation Member.	PICASSO platform member. Asked for a derogation for the connection until July 2024.	MARI platform member. Asked for a derogation for the connection until July 2024. TERRE platform active member.

TABLE 22: BALANCE SERVICES STATUS FACTS SHEET IN SPAIN.

3.3 SOCIETAL CHALLENGES

The societal acceptance of energy storage systems can be a significant barrier to the mass adoption of these technologies, particularly but not restricted to smaller assets participating in distributed systems offering flexibility services to the grid, whose penetration in the energy system may be dependent on the participation of active consumers, who nowadays are regular citizens who tend to organize themselves into energy communities which in turn participate in larger pools through aggregation. The ESS are associated to clean and modern energy technologies as vehicles to decarbonize the electricity system by supporting distributed renewable energy generation and, for example, enabling cost effective electric vehicles. Regarding the latest, the visibility of the worldwide high growth of EVs market is raising concerns regarding the life cycle of batteries, the scarcity of materials for manufacturing, and the socio-economic impact of their exploitation. In general, societal acceptance of storage technologies, is related with the perception and the interrelation of the ecosystem and environmental and socio-economic impacts from the production of the devices to their end-of life, and usage safety and health effects.

3.3.1 Perception and public acceptance

A clear example of direct impact on environment are the hydroelectric systems that change profoundly the ecosystems. Large installations, such as PHES installations require the creation of artificial reservoirs that impose, in a very short-term period, a dramatic change on the natural ecosystem, risking local flora and fauna species. The large water reservoirs also affect the surrounding climate, that often impacts by creating local socio-economic crisis affecting agricultural and other land use related economic activities. In some cases, this impact is overcome by fomenting new local economies related with new aquatic resources, such as leisure and recreation activities and tourism. In addition, the orography modification of the sites is perceived as having an important visual impact, also associated with heritage identity losses. The same occurs with the new transmission systems for electricity that have to cross long distances through natural ecosystems to connect the hydroelectric plant to the populations.

The perception of security of the usage is probably the most decisive barrier in technological adoption processes by the public. After the early adoption phase, the usage acceptance of a system can be highly affected by reported experiences of operational hazards, accidents, etc. In general, energy storage technologies are perceived as non-mature technologies, and with high probability of failure [146], e.g. the high flammability of hydrogen has been hindering the market perception and the use in the automotive or house hold applications. A similar example are the electrochemical batteries namely, Li-ion used in electric vehicles [147]. Episodes of failures without vehicles' crash, producing strong exoenergic events, related with battery managing system promote the perception of technological immaturity, which is even more associated with the systems safety in case of crash of the vehicle.

3.3.2 Materials dependency and LCA

Among the energy storage technologies electrochemical and chemical batteries manufacturing are probably the most material intensive. Despite efforts to replace rare and scarce materials, some elements with specific properties, such as electrochemical potential and medium solubility, are irreplaceable. The uniqueness of these elements often introduces high pressure into the usually very concentrated supply chains as result of material criticality, which raises the stock prices and imposes geopolitical issues and power unbalances. Locally, the socio-economic impacts are created by land usage, unfair competition and additional environmental problems, such as, contamination of water resources.

The scarcity and high dependency of raw materials nexus in Energy storage was already target by European commission in [148], concluding the need to develop more resilient value chains for European industrial sectors by following basic principles as to:

- (1) reduce dependency on primary critical raw materials through circular use of resources, sustainable products, and innovation.
- (2) strengthen the sustainable and responsible domestic sourcing and processing of raw materials.
- (3) diversify supply with sustainable and responsible sourcing from third countries, strengthening rules-based open trade in raw materials and removing distortions to international trade.

Identified in the EC report [149] the most critical elements grouped by energy storage technology can be seen in Figure 32. As stated before, electrochemical storage systems are the most dependent on critical elements, with a distinct expression of Li-ion batteries.

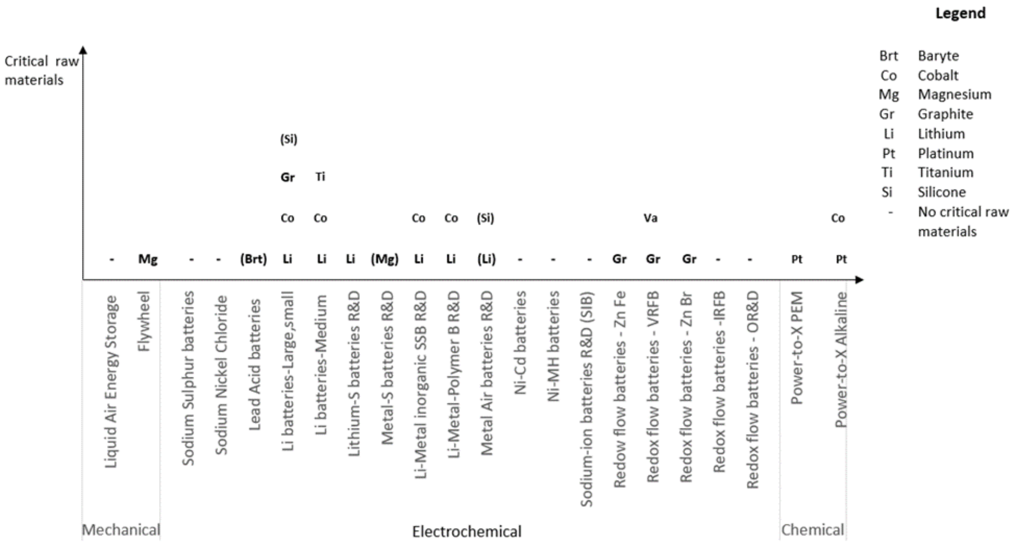

FIGURE 32: CRITICAL ELEMENTS USED IN ENERGY STORAGE TECHNOLOGIES.

According to the previous principles, storage supply chains' resilience can be increased. It is necessary to keep improving the processes addressing the "cradle to grave", from the extraction of minerals to extending the life of the devices and recycling them at the end of their life. However, the technological complexity of the storage technologies encompasses enormous challenges to reuse them or recycle them. The life cycle analysis (LCA) framework is an important tool to trace and track all the related aspects during the useful life of the devices. LCA is defined by the International Standard ISO 14040:2006 (2006), as instrument to assess and evaluate the environmental and potential impacts of any product, process, or, from the early development stages, i.e. extraction of raw materials to its end-of-life, eventually dismantling and recycling (Figure 33).

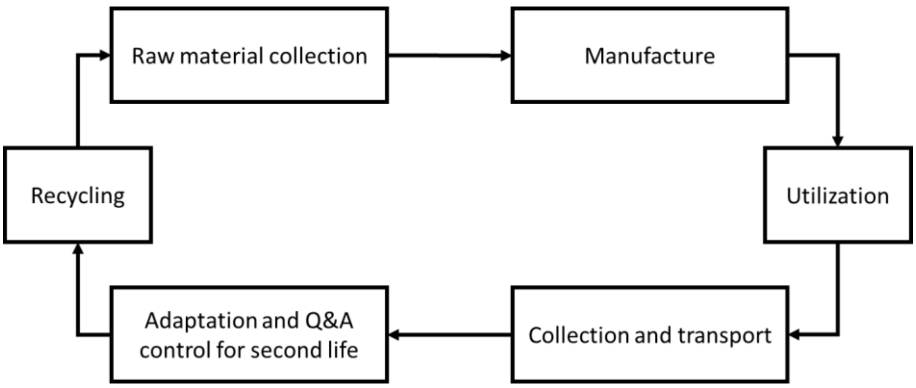

FIGURE 33: LCA FLOW OF ELECTROCHEMICAL BATTERY.

The materials used and residues produced along the whole value chain, impose another important public perception barrier concerning the hazardous health effects related to the use of heavy metals mainly in the battery's technologies. In fact, several heavy metals used in these devices such as cadmium and lead, are classified as cancerous substances by the European Commission [149]. Direct exposure to such materials could be through leakages in electrolyte containment and atmospheric gas emissions, so the use of these materials should be minimized. LCA is, also in this matter, an important traceability tool to track toxic components and exposure levels over the lifetime of devices.

3.3.3 Second-life batteries

The concept of second-life usage of BESS after its initial application has been gaining attention in the last recent years [150], contributing to the public perception of the impacts of the technologies' life cycles. BESS, for example, in the context of electric automotive industry, when degrade at the standards for usage limits, typically maintain up to 80% of their total usable capacity or daily self-discharge inferior to 5%, must be replaced. Global fast growth of electric vehicles is an opportunity for stationary storage, which could exceed 200 gigawatt-hours by 2030 [151]. The systems are then disassembled to the level of modules or cells, and after tight quality and safety assurance procedures are reconditioned in new designs meeting the second life applications requirements in terms of voltage and power rates. Second life-batteries batteries could generate significant value and benefit the grid-scale energy storage market. Of course, as depreciated assets for EV application, a proper assessment of the potential application as to be done (Figure 34).

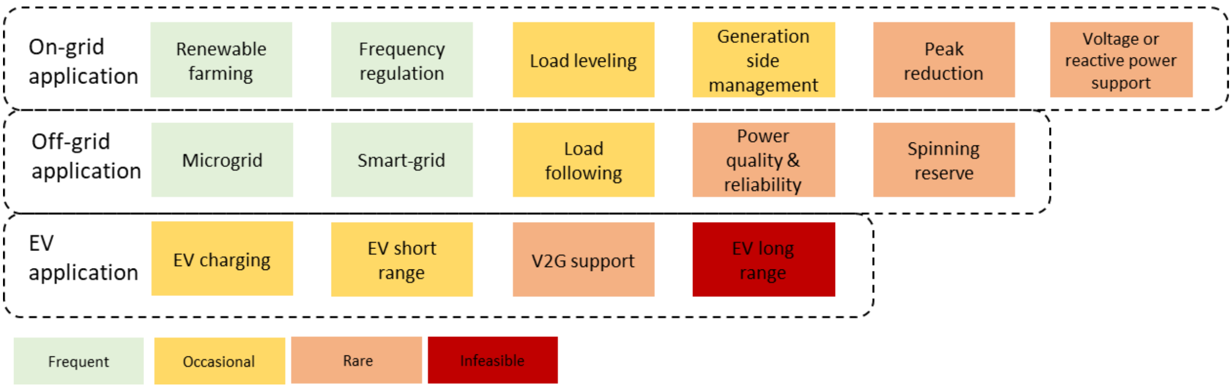

FIGURE 34: SECOND LIFE-BATTERIES (SLB) POTENTIAL APLICATIONS CLASSIFIED BY FREQUENCY OF APPLITATION AND LEVEL OF FESABILITY [152].

However, several technological and regulatory challenges remain for second-life batteries applications to grow at large scale. Furthermore, the refurbishing processes can be costly, and a lack of standardization and streamlining quality procedures is still hurdling second life batteries while not achieving economies of scale. Common certification, standardization, and warranty liability regulations for repackaging of used modules is needed to overcome these challenges.

3.4 FINAL REMARKS

Energy storage systems are undoubtedly a key part of the solution to meeting the EU's carbon neutrality targets for 2035 and 2050, providing system operators with the ability to manage and operate the large amounts of clean energy produced by distributed energy resources in a secure and resilient system. The benefits of integrating storage into the grid are clear and well identified, starting with providing the versatility and flexibility required by the system that other demand-side resource services are not able to provide, such as energy shifting for different time scales ranging from the second to seasonal periods. The integration of ESS into the system can avoid grid reinforcement costs and contribute to operational costs. The technological diversity and modularity have been opening new opportunities for new roles, such as aggregation and active consumers, by offering unique flexibility functionalities.

Despite the widespread recognition of energy storage technologies, several persistent obstacles are still preventing their full deployment, hurdling the development of sustainable business propositions, which are essential to support the widespread adoption of these systems across different scales and markets, and ultimately conducting to the completion of the energy transition. Having in the background the hindrance imposed by a constantly changing and adapting national and common regulatory frameworks, there are other practical barriers, such as technological readiness and adequacy of technologies and their availability on the market, issues with capacity and energy market designs, and the societal perception of energy storage that impose important resistance factors for the massive adoption of this technology.

Another technical barrier worth highlighting, which is not intrinsically related to the maturity of energy storage technologies, is the existence of information networks for the transmission of metering data required by the system operators to participate in the markets. This technical requirement constitutes one of the main entry barriers for participation of smaller storage assets in capacity and power markets, even when aggregated, since the investment in certified communication lines can represent an impeding burden for the initial investment capital of small providers and aggregators. This barrier is even more relevant in the context of the proliferation of distributed systems and in a context where the resilience of the grid depends on the proliferation of distributed capacity and demand response flexibility services.

Regarding energy market barriers, a wide range of services based on functionalities in which energy storage systems are particularly suited for, such as black start, voltage regulation, reactive power, and congestion management, are not yet developed in most European countries, or are not procured by market-based mechanisms. New market designs need to be further developed ensuring that these services are procured from low-carbon sources to support the grid, while guaranteeing appropriate remuneration to make them attractive for investors and developers. The access to spot and balancing markets by storage operators is not granted and some progress on regulatory frameworks for the procurement of flexibility by TSOs is further required. Also, the introduction of appropriate contracts for services procured by system operators allowing value stacking by storage operators should be further addressed. ENTSO-E cooperation projects between the EU region have been setting an important basis, allowing to test and integrate new balancing market rules and standards, to ultimately transform the balancing energy markets from fragmented national to a harmonized pan-European one, ensuring compliance with the recommendations of the Electricity Balancing Guideline and the technology neutrality principles of the Electricity Market Directive. However, there is still a long way to go to enable the participation of storage assets as well as other demand-side flexibility services. System operators should improve the long-term vision for flexibility needs in Europe. Many balancing services are limited to energy-only auctions and re closed to aggregation. Long term contracts, are seen as a solution that could stimulate private investments, functioning as guarantees for project developers, while allowing other short-term product stacking increasing the revenue streams of storage applications.

Social acceptance of storage technologies also presents its own challenges for storage market growth and mass adoption. Among the factors affecting the public perception of energy storage technologies, security and the socio-economic and environmental impacts of the entire value chain are highlighted as the main obstacles. Increasing transparency on the impact along the entire value chain, from the exploration phase of materials, through use and end-of-life processing, by investing in LCA and social LCA, as well as safety disclosure, can improve this barrier. In turn, the re-use of second-life batteries is addressed as a publicly recognized solution to minimize the impacts of intensive material dependence on scarce elements used in the production of some energy storage technologies, in particular chemical and electrochemical batteries.

4 SURVEY ON STORAGE INTEGRATION: STATE-OF-AFFAIR AND REGULATORY BARRIERS

This section describes and assesses the result of a survey executed across five countries. Stakeholders from Spain, Slovenia, Portugal, Italy and Greece were asked to give their evaluation of their respective countries' state-of-affair and regulatory barriers, in order for Task 2.2 to assess the overall situation in the I-STENTORE pilot countries.
We received replies from a DSO as well as a consulting SME and a manufacturer in Spain, 4 DSOs, a TSO as well as the national regulatory authority in Slovenia, a DSO and a DSO/TSO in Portugal, a DSO/Multiutility entity in Italy, and one research organization in Greece.
In the following, the received replies are consolidated by country. Subsequently, an assessment of the individual topics across the surveyed nations is made, followed by an overall conclusion regarding implications for I-STENTORE's upcoming work.

4.1 SUMMARY BY COUNTRY

The following subsection consolidates the answers received by country and type of stakeholder.

4.1.1 What is the general policy motivation for deploying storage in your country?

Spain
Storage technologies are necessary to account for the volatility of weather-dependent power generation. Their integration helps to ensure that an expansion of renewable energy use still allows for a flexible, robust and resilient grid while keeping market prices manageable.

Slovenia
In Slovenia, the motivation for introducing battery systems depends on the stakeholder in the electricity market or with its activity and the interest that pursues. For example, TSO already uses large battery systems for frequency recovery backup with automatic activation and frequency recovery backup with manual activation. (FCR, aFRR, mFRR)
In the context of the distribution network, the issue of network overload can be mitigated by integrating electricity storage devices at the measuring points where electricity is generated. By deploying such devices, distribution operators can effectively regulate voltage and alleviate peak loads on the network. Additionally, these batteries, capable of island operation, can serve as backup during short-term outages in the distribution network.
Prosumers, on the other hand, can leverage home battery systems to store surplus electricity generated by small-scale solar power plants under net metering schemes. These stored surpluses can then be utilized during periods of high electricity prices. While there is a considerable number of such batteries in Slovenia, a larger-scale deployment is anticipated after 2024 when legislation changes will shift net metering calculations from an annual to a monthly basis.
Energy policy encourages installation of electricity storage devices. Household customers receive additional subsidies if they build their own solar power plant with storage capabilities. Customers who own energy storage devices are not charged network fees and other costs for the delivered energy previously stored on their premises. When providing flexibility services for electricity operators, no network fee and other costs are charged for the transmitted or received energy stored in the premises of active customers.
However, several obstacles hinder the widespread implementation of battery systems. These include the high cost of such systems, limited capacity, and relatively short lifespan. Additionally, a lack of experience in connecting batteries for island operation poses another challenge.
Regarding legislative barriers, there is a specific restriction for TSOs and Distribution System Operators (DSOs) in owning battery systems for system service purposes. Although exceptions are allowed under certain conditions, the regulatory authority has yet to define clear criteria for these exceptions. Consequently, the current option for system operators is to procure these services from the market.

Portugal
The exercise of the storage activity of Madeira's regional electricity system, under the public service regime, is developed exclusively by EEM. On the other side, the storage activity, under the special regime, is developed, in a regime of free access, by Special Regime Producers, under the terms established in the regional legislation.
Even though there is not yet a specific legal framework in this field in Portugal, energy policy places a strong focus on achieving economy-wide decarbonisation through broad electrification combined with rapid expansion of renewable electricity generation. Portugal's National Energy and Climate Plan (PNEC/NECP) sets 2030 targets for emissions reductions,

energy efficiency and renewable energy that aim to put the country on a path towards achieving cost-effective carbon neutrality by 2050.
The Autonomous Region of Madeira's Action Plan for Sustainable Energy and Climate (PAESC-RAM), which is aligned with National and European policies, defines the objectives and targets for the timeframes until 2030 and 2050 in the areas of Energy and Climate, in accordance with the Regulation (EU) 2018/1999 of the European Parliament and of the Council, and with the PNEC/NECP.
PAESC-RAM deals directly with the topic of storage - mostly where energy security and uninterrupted availability of energy sources are concerned.
Other motivations include the Regional Government of Madeira strategy of maximising the use of renewable energy sources, improving the efficiency of the electric generating system and reducing CO2 emissions by turning off diesel thermal generators, more renewable energy integration and thus resulting in less curtailment of RES production, and the political aim of achieving 50% of RES production by 2025 and between 55%-60% by 2030.

Italy
The main motivation arises from the importance of storage technologies for the deployment of variable energy production from RES.

Greece
There are several policy motivations for deploying storage in Greece, including:

- Integration of Renewable Energy Sources: Greece has set ambitious targets to increase the share of renewable energy sources in its energy mix, and energy storage can help integrate intermittent sources like wind and solar power by storing excess energy when it's available and releasing it when it's needed.
- Energy Security and Reliability: Energy storage can help improve energy security and reliability by providing backup power during grid outages and reducing dependence on fossil fuel imports.
- Grid Stability and Flexibility: Energy storage can help balance the supply and demand of electricity on the grid by providing additional power during periods of high demand and reducing the need for peaker plants, which are often expensive and polluting.
- Energy Cost Savings: Energy storage can help reduce energy costs by allowing consumers to use stored energy during times of peak demand when electricity prices are highest, and by reducing the need for expensive grid upgrades.

Overall, the deployment of energy storage in Greece can help the country achieve its energy and climate goals, improve energy security and reliability, and reduce energy costs for consumers.

4.2 STRATEGY/TARGETS

4.2.1 Does your MS have a separate storage strategy or it is only in the NECP/national energy strategy

Spain

- Estrategia de Almacenamiento Energético

Slovenia

- Integrated National Energy and Climate Plan of the Republic of Slovenia (NEPN)

Portugal

- An overall storage strategy is being prepared by the Portuguese government
- Specifically to the isolated grid of Madeira: Autonomous Region of Madeira's Action Plan for Sustainable Energy and Climate (PAESC-RAM)

Italy

- No, only NECP

Greece

- No, only NECP

4.2.2 If so, what is the key target for

4.2.2.1 Power system flexibility (by which year?)

Spain
No answer

Slovenia
Accelerated installation of storage systems (including pumped-hydro, H2, waste-heat utilization and battery storage systems) by the year 2030. The goal is to achieve that the share of storage systems in the daily consumption diagram is the equivalent to the share of solar and wind production in the yearly consumption of electrical energy. For frequency services acceleration of battery storage systems is foreseen, although no exact figures are provided.

Portugal
No specific goals are known yet.

4.2.2.2 Storage (by which year?)

Spain
No answer

Slovenia
The NECP has foreseen installation of battery storage systems alongside new solar PVs, where the battery system has at least 25% of installed power compared to the installed power of the solar PV from 2024 onwards.

Portugal
No specific goals are known yet.

4.2.3 What – do you think – is a barrier to storage development in your country from the strategic aspect?

Spain

- High cost of solutions
- Energy auction leveraging in favour of larger operators
- Regulations limiting access of SMEs to some markets
- Slow bureaucracy and permitting

Slovenia

- DSO:
    - No aggregators in the market to offer battery systems as a service
    - Price of storage technology, lack of subsidies or other types of incentives
    - Underdeveloped business models for small-scale storage technologies
    - Sub-optimal state of technology with battery storage and H2 (short lifetime, low efficiency, self-depletion, etc…)
    - With pumped hydro, difficult processes of placing infrastructure in the environment.
- TSO:
    - Storage providers are actively operating on the services and energy markets. They are partly providing these services through large scale storage units and partly through aggregation of small size units
    - Regulatory Authority:
    - Governmental interventions for mitigation of the negative impacts of energy crisis (price caps set on the system services markets)
    - Insufficient observability of distribution grids
    - Lack of flexibility register
    - Directive MID hindering the development of submetering
    - Independent aggregator model (IAM) needs patching

Portugal

- High cost without capacity incentives for the investors in a barrier
- Technical and logistical barriers for small-scale isolated electrical systems, e.g. Madeira
- Bureaucracy:
    - Possible restrictions arising from spatial planning and protected areas, mainly environmental permits
    - The need for approval of structural investments and tariffs by the Regulator (ERSE-Energy Services Regulatory Authority)
- Lack of specific legislation regarding the business model

Italy

- Strong dependence on foreign countries in the supply of critical components
- High costs of storage systems

Greece

No answer

4.3 REVENUE STACKING AND COORDINATION

4.3.1 Can storage owners stack revenue (multi-use application) from multiple sources? If no (not fully), what are current reasons that hinder the operation?

Spain
Yes, except not all markets are fully accessible

Slovenia
Not fully: rules for market operation needs an update in the domain of IAM.

Portugal
Yes, but there is a lack of specific legal and regulatory framework in this field and for providing ancillary services with storage assets.

Italy
Yes

Greece
Yes, storage owners in Greece can stack revenue from multiple sources, allowing them to participate in various energy markets and maximize their return on investment. This is supported by the regulatory framework in Greece, which allows for multiple use cases and revenue streams for energy storage systems, including providing grid services, participating in the wholesale electricity market, and enabling behind-the-meter services for commercial and residential customers.

4.3.2 Is there a coordinated process of how DSOs and TSO can use storage? If so, please, describe.

Spain
No

Slovenia
Currently no, because DSO system services markets are not yet developed on the commercial scale, only on the demonstration level. But there are plans for coordinated activation of flexibility sources (also from storage systems) between TSOs and DSOs in Slovenia in the future. Also, for connecting any storage systems in DSO networks the owner of the usage point has to obtain a connection agreement.

Portugal

Not yet, because there isn't significant storage connected to the distribution grid.

Italy
Yes, TSO and DSO collaborate within the capacity market-based process. The capacity market is part of a National and European framework that aims to make the electricity market more efficient and open to new supply resources, to better integrate renewables, storage systems and demand management, while ensuring system security.

Greece
There is not currently a coordinated process in place for how DSOs and TSOs can use storage in Greece. However, there are ongoing efforts to develop more coordinated approaches to the deployment of storage in the grid. For example, the recent transposition of the EU Clean Energy Package into Greek law has introduced provisions to facilitate coordination between DSOs and TSOs, with the aim of promoting the more efficient use of storage and other flexibility solutions. Additionally, pilot projects and demonstration activities are being carried out to test and evaluate new approaches to coordination and revenue stacking for storage owners in Greece.

4.4 ARE THERE BARRIERS WITH RELATION TO POWER MARKETS (WHOLESALE MARKET SUCH AS FORWARD, DAY AHEAD, INTRADAY AND CAPACITY MARKETS)

Spain
- Market rules (e.g. bid size, durability requirement, price caps, bid formats, derating factors etc.)
- There are regulations in terms of minimum capacity, duration of the service…

Slovenia
None

Portugal
- Missing aggregators for small storage

Italy
None

Greece
- Market-base price formation: The current price formation mechanism for power markets in Greece can create barriers for new entrants to the market. For example, price caps may limit the potential revenues that can be earned from selling electricity, which can make it less attractive for newer technologies such as renewable energy sources to participate in the market.

Co-funded by the European Union

- Market entry: There may be barriers to market entry for new generators or retailers in Greece. This could include regulatory requirements such as licensing and qualification requirements that may be difficult for smaller players to navigate.
- Market rules: The current market rules for power markets in Greece may not be conducive to the effective participation of newer technologies such as renewable energy sources. For example, inflexible contract durations or a lack of price signals that reflect the full value of these technologies can limit their potential to participate in the market.

4.5 ARE THERE BARRIERS WITH RELATION TO ANCILLARY SERVICES?

Spain

Same as the barriers for power markets

Slovenia

- Price formation: Price cap on aFFR system services market based on the intervention of Government applying measures for mitigating the impact of energy crisis
- Market rules: IAM needs an update in order to better specify the rules for the participation in the local flexibility markets (incl. distribution non-frequency system services and congestion management).

Portugal

- Price formation: The electricity sector is totally regulated, and there is no tariff for this kind of service.
- Market entry: Since 2020, EEM under the public service regime and only manager of the SEPM, has deployed in the Autonomous Region of Madeira large scale energy storage systems using batteries and hydro systems, that provide ancillary services to its electrical grids in a centralized way (Madeira Island and Porto Santo Island), and, for now, these ancillary services are already assured.
- Minimum bid size of 1 MW

Italy

- Yes, there are regulatory barriers for ancillary services

Greece

- Price formation: The current price formation mechanism for ancillary services in Greece is complex and can create barriers for new entrants to the market. For example, price caps may limit the potential revenues that can be earned from providing ancillary services, which can make it less attractive for newer technologies such as energy storage and demand response to participate in the market.
- Market entry: There may be barriers to market entry for new providers of ancillary services in Greece. This could include regulatory requirements such as licensing and qualification requirements that may be difficult for smaller players to navigate.

- Market rules (e.g. bid size, durability requirement, price caps, bid formats, derating factors etc.): The current market rules for ancillary services in Greece may not be conducive to the effective participation of newer technologies such as energy storage and demand response. For example, inflexible contract durations or a lack of price signals that reflect the full value of these services can limit their potential to participate in the market.

4.6 NETWORK USE AND MANAGEMENT (DISTRIBUTION AND TRANSMISSION)

4.6.1 Is there any flexibility platform available in your country (e.g. Piclo, Nodes)?

Spain
No.

Slovenia
Yes, however each TSO and DSO has developed its own flexibility platform. There is a common platform under development. Aggregators and BSPs also use their own flexibility platforms.

Portugal
Piclo in use by at least one DSO

Italy
No.

Greece
Currently, there is no specific flexibility platform available in Greece, such as Piclo or Nodes. However, there are several initiatives underway to enable flexibility trading and management, including pilot projects for peer-to-peer energy trading and demand response programs.

4.6.2 Do you have locational and temporal network tariffs for consumers/producers/storage? Any barriers due to network tariffs (e.g. double charging)?

Spain
No.

Slovenia
Slovenian legislation allows for special network tariffs for implicit flexibility, which can be local. If, for example, in a certain part of the low-voltage network, there is no flexibility offered by the market, the DSO itself can initiate a DR program with the help of critical peak tariff tariffs, which serve as an incentive for demand adjustment. To implement such a program, it is

necessary to obtain prior permission from the regulatory authority. There is a 2-tariff system in place with a high- and low-tariff. Customers can also opt to use only 1-tariff. From 2024 the new tariff system comes into effect with a maximum of 5 tariffs within the year, with a maximum of 3 tariffs during the day. This is also the basis for implementing a dynamic tariff system foreseen in 2030.
Currently no barriers due to network tariffs. However due to the low number of storage assets in the systems, especially those connected to DSOs network, there is currently a big lack of good and bad practices. We assume, when the number of storage assets will grow, these barriers will become more evident.

Portugal
No.

Italy
No.

Greece
Greece has implemented locational and temporal network tariffs for consumers, producers, and storage. These tariffs are designed to encourage the efficient use of the electricity grid and to reflect the costs of grid usage. For example, consumers who use the grid during periods of high demand or in locations where the grid is constrained may pay higher tariffs than those who use the grid during off-peak periods or in less congested areas.
While network tariffs are intended to promote efficient grid usage, they may also create barriers to the deployment of distributed energy resources (DERs), such as solar PV and energy storage. For example, some network tariffs may double-charge DER owners for using the grid to export excess energy back to the grid. This can make it less financially viable for consumers and producers to invest in DERs.

4.6.3 Any barriers due to connection procedure?

Spain
No.
Slovenia
No (all but one).
Answer from one DSO: Yes. Currently a storage device is considered as a generation device, where the owner of the usage point has to obtain a connection agreement. Connection agreements are in turn dependant on the hosting capacity of the network, where the storage asset is being connected.

Portugal
Only the RfG European code requirements

Italy
Very long permitting lead time

Greece

The connection procedure for DERs in Greece can be complex and time-consuming, which can create barriers to their deployment. In some cases, the connection procedure may involve multiple steps, such as obtaining permits, conducting studies, and negotiating interconnection agreements with the network operator. These procedures can also involve significant costs for the DER owner, which can further discourage investment in DERs.

4.7 NETWORK OPERATORS

4.7.1 Are network operators incentivised to procure flexibility?

Spain
No.

Slovenia

- TSO: Yes
- DSO: No. Currently flexibility is not yet applied for the needs of distribution networks

Portugal
Yes, e.g. EEM as TSO/DSO in Madeira Archipelago has been developing several studies, pilots and real-lab demonstrators for the flexibility issues, and some are co-financed by European Union research and innovation funding programs.

Italy
No.

Greece
The network operators in Greece are incentivized to procure flexibility through various policies and regulations. For example, the country has introduced a competitive bidding process for capacity procurement, which allows flexibility providers to compete for contracts to provide services such as demand response, energy storage, and virtual power plants.

4.7.2 Do they have counterincentives?

No participant reported any concrete counterincentives.

4.7.3 Are they transparent on the locations and volume of flexibility they would need to deal with congestion?

Spain
No.
Slovenia
TSO yes, DSO no

Portugal

No.

Italy

There are some experimental project to evaluate the hosting capacity due to the flexibility in the distribution grid.

Greece

The network operators in Greece are required to be transparent about the locations and volume of flexibility they need to deal with congestion. This information is typically provided through various tools and platforms, such as hosting capacity maps, network development plans, and grid codes.

4.7.4 What are the tools they provide this information (e.g. hosting capacity maps, network development plans assessing both wire and non-wire solutions etc.?

Spain

There are no flexibility markets for DSOs nowadays in Spain.

Slovenia

Currently, the biggest problem in Slovenia regarding the implementation of flexibility is that there is no offer on the market. Pilot projects under Horizon and national projects are currently in plane in the area. There is a so-called hosting capacity map in Slovenia, but it is not primarily intended for the market with flexibility, but as a guide for investors, where they can place production units in the distribution network.

Portugal

Network development plans are public

Italy

No tools for DSOs at the moment.

Greece

The Hellenic Electricity Distribution Network Operator (HEDNO), which is responsible for the distribution of electricity in Greece, provides various tools and platforms to provide information on the locations and volume of flexibility needed to deal with congestion. These include:

- Hosting Capacity Maps: HEDNO has developed hosting capacity maps that provide information on the capacity of the grid to accommodate renewable energy sources and other distributed energy resources.
- Network Development Plans: HEDNO publishes a network development plan every two years that outlines its investment priorities and identifies potential locations for new network infrastructure.
- Grid Codes: HEDNO's grid codes provide technical specifications for connecting to the grid and operating grid-connected systems, and include information on the requirements for providing flexibility services.

Overall, while there may be some counterincentives for network operators in Greece, there are also policies and regulations in place to incentivize the procurement of flexibility. Network operators are required to be transparent about their needs for flexibility and provide information on the locations and volume of flexibility needed to deal with congestion through various tools and platforms.

4.8 BEHIND-THE-METER STORAGE

4.8.1 Any barriers related to tariffs (e.g. net metering)?

Spain

No.

Slovenia

Net metering was a big suppressor of domestic storage installations, which is still in effect for all existing PV installation, and for future PV installation which will be connected until the end of 2024. However, with the new tariff system coming in effect in 2024, we do not see any more specific barriers. The biggest remaining barrier is a suitable business model for domestic users to prefer PV+storage investments compared to other money-saving projects such as house insulation, heat systems change etc. For businesses, the situation dramatically changed with energy price spikes in the end of 2021 and throughout 2022. Businesses were not eligible to enter net-metering, so they never consider it in economic calculation. Main incentives for businesses to decide for PV (and storage) are lowering grid utilization by lowering amount of purchased MWh and lowering peaks. Net metering is used in possible for household customers and small business (with connection capacity for consumption lower than 43 kW). Until the end of 2023, for users who are connected according to the net metering scheme, it does not make sense to purchase battery systems, since they are on an annual billing, as the distribution network "stores" their surpluses. After 2024 this legislation will change, and it will make sense for such users to purchase a home battery system.

Portugal

Responses differ, but those that stated that barriers do exist did not elaborate on their cause.

Italy

DSOs can't impact the tariffs. There is no regulation in the market place based on the ancillary services for DSOs.

Greece

The current net metering policy in Greece does not provide a favourable tariff structure for energy storage systems. Under the current policy, excess energy generated by rooftop solar panels can be sold back to the grid at a lower rate than the retail price of electricity, which may discourage investment in energy storage.

4.8.2 Any barriers related to the installation of storage?

No participant reported specific barriers particularly related to installation.

4.8.3 What is the current deployment level of behind-the-meter storages?

Spain

Hybridisation of storage with other technologies is possible if the operator allows it

Slovenia

Low. Only for frequency services, in an aggregated manner, and only one business model driving the deployment has been identified (https://www.ngen.si/)

Portugal

Almost none.

Italy

No specific regulations, actual level of deployment unclear.

Greece

While there are some policies and regulatory frameworks in place to support the integration of battery storage technologies, there is still a need for more comprehensive and consistent policies that address issues such as grid interconnection, energy storage standards, and technical requirements.

4.9 ARE THERE POLICIES OR REGULATORY FRAMEWORKS THAT SUPPORT THE FURTHER INTEGRATION OF BATTERY STORAGE TECHNOLOGIES?

Spain

Yes. Spanish government has approved energy storage strategy targeting 20 GW by 2030 and 30 GW by 2050.

Slovenia

Yes, Slovenian Act on the methodology for determining the regulatory framework and the methodology for calculating the network fee for electricity operators which is expected to take effect in the beginning of the year 2024.

In particular the new network tariff reform introduced by Slovene Energy Agency planned to enter in use 1st of January – it contains strong signals for integration the battery storage behind the meter (self-consumption), it assures level playing field to storage when participating in flex markets, possibility to adjust the charged power according to planned economic dispatching, and more … Some additional improvements are already designed and planned to be introduced soon in order to provide the incentives for portable storage providing non-frequency system services and CM services to DSO.

Portugal

Unclear - the policies and regulatory framework for storage are changing and in development

Italy

No.

Greece

While there are some policies and regulatory frameworks in place to support the integration of battery storage technologies, there is still a need for more comprehensive and consistent policies that address issues such as grid interconnection, energy storage standards, and technical requirements.

4.10 ANY OTHER BARRIERS? (E.G. DEFINITION, STAKEHOLDER RESPONSIBILITY PROBLEMS, PUBLIC SUPPORT ETC.)

Spain

None given.

Slovenia

When implementing system batteries, problems with citizens are expected due to the so-called NIMBY (Not In My Back Yard) phenomenon.

There is no public support for domestic installations since the systems are too expensive (no good ROI). Moreover, we see a lot of scepticism among people in the technology for both, storage and transportation. Much more would need to be done to change public opinion, which is now determined by newspaper commentators. Additionally, the country needs to let public know which investments they want to support: commercial, domestic or both so businesses and households can calculate their budget and see what suits them. Especially household future electricity prices and investment focus is very unclear at the moment due to the end of net metering scheme.

Specific implicit barriers – collisions between CEP and MID hindering the development of submetering etc. Slovene Energy Agency triggered the analysis and asked for action at the EU level in order to remove normative barriers.

Portugal

- Big issue: international market price volatility of raw materials and overall solutions
- Incompleteness and currently ongoing development of regulatory framework

Italy

None given.

Greece

Other barriers to the deployment of energy storage in Greece may include lack of access to financing, limited public awareness and education, and uncertainty around future energy and climate policies.

4.11 ASSESSMENT OF SURVEY RESULTS

The following is an assessment of the survey results consolidated across all countries, looking into common issues and overall insights regarding the surveyed topics.

Initially, it becomes quite clear that the development in the field of storage integration is generally motivated by similar factors: Stability and flexibility, security and reliability of the energy grid is of course a vital subject regardless of location or nationality. While individual additional circumstances arise, it is no surprise that the integration of renewable energy and energy cost savings are of interest to any entity hoping to be well-equipped for the ongoing shifts in the world's energy systems.

Within the framework of the EU and the NECPs, countries are moving in this direction. However, individual strategies in addition to the NECP are rather scarce, and those that exist do not always have clearly defined KPIs.

Across the surveyed countries, the main barriers for storage development are expensive solutions in combination with lack of both subsidies and business models to make up for those costs. Regulation hinders development by being slow on permitting, and in some cases ambiguous or outdated regarding the rules for businesses.

In three of the five regarded countries, market regulation significantly hinders revenue stacking, mostly by curtailing accessibility through lack of a specific framework for this type of trade, or by existing rules being outdated and creating issues as a result. Coordination of storage use between TSOs and DSOs is not properly in place anywhere but in Italy - interest in increased activity exists, however the low level of storage deployment on distribution level results in this issue not receiving a high priority in these areas.

In the context of power markets, the barriers most prominently mentioned across the received answers are barriers to market entry. This includes minimum requirements (capacity, duration of service, etc.) keeping smaller stakeholders out of these spaces, as well as complicated bureaucracy which can repel potential new participants. Within the market operation itself, lack of flexibility in regulations poses an additional barrier for the exploitation of new technologies.

Ancillary services on market level face many issues similar to those on the power market. In particular, minimum stakeholder requirements limiting the accessibility of markets to new participants, and regulations being inflexible and outdated impede efficient trading and development of new business models. In addition, price caps are in place in some of the surveyed countries, which limit the attractiveness of already cumbersome market participation for potential newcomers.

The application of flexibility platforms differs between as well as within nations. Where they are in use, there does not usually seem to be an agreement or a standard of choice.

Similarly, the situation regarding network tariffs is very diverse across the surveyed countries. Where they are in place, the existing rules are not necessarily well-adjusted to everyday operation of new technologies (yet), and may raise barriers as a result.

Italy and Greece in particular reported significant barriers within the connection procedure, citing especially long approval times and complex processes.

Existing incentives for flexibility development are mostly limited to TSOs. While quite established particularly in Greece, participants from the other four nations reported a distinct lack of them, specifically regarding DSOs. However, there also weren't any counterincentives listed in the context of this survey.

Regarding transparency, across the received replies spans the notion that a lack of projects and activity in this area limits the need for sharing tools such as hosting capacity maps.

Tariff-related barriers across the surveyed countries are diverse, but overall limited compared to other issues. The regulations in this area are in transition at the moment, moving in a direction beneficial for increased domestic behind-the-meter-storage.

In the context of storage installation, no participant of the survey named any concrete barriers. Nevertheless, all of them reported a very low level of existing behind-the-meter storage deployment. The most likely reason for this apparent contradiction is the high cost and low return for an individual household in purchasing storage technology. Policies and regulatory framework incentivizing their increased integration are partially in place, but not widespread yet. However, they are generally moving in the direction of more rather than less storage incentives.

Barriers not specifically requested by the survey concern two main issues: public acceptance and volatility of the overall situation.

Public acceptance is important for the widespread adoption of storage technologies, and it is hindered by lack of education and awareness in combination with complicated regulations, as well as high cost of installing domestic storage technologies and few established business models.

Volatility is an issue both in market pricing and in general regulation. Raw materials and overall solutions both have fluctuating prices due to the continuously evolving state of the art in technologies themselves, as well as a variety of uncertainties on world markets in the current time. Regulations must adapt to the rapid speed of technology development and political requirements, and as they are (as established) quite behind on some issues, they need to evolve and change continuously. However, as they do, it becomes hard for stakeholders to rely on frameworks and have planning security for future endeavours, making the very effort of adjusting regulations to their needs a barrier in development.

4.12 CONCLUSION AND IMPLICATIONS

Across the board, the results of this survey make it clear that regulatory barriers for the development of storage technologies and strategies are a recognized issue across the landscape of all five countries, and are being addressed with quite different degrees of success.

The fast pace of technology and business development on the ground are a main cause for the existing issues with regulation: The organizational frameworks of markets and network operations cannot keep up with development of technologies and stakeholder requirements, and as a result many existing rule sets and policies are either outdated and therefore not taking into account the reality of new and flexible stakeholders, or they are new and not yet fully refined to everyday circumstances. However, developments can be observed that incrementally improve on these problems.

In addition to the individual barriers themselves, their inconsistency across different countries causes obstacles for multi-nation projects such as I-STENTORE. Developing a solution flexible enough to take into account this diverse landscape of regulations and customs is a challenge, especially with the aforementioned ongoing changes and volatility in the situation.

Regarding the I-STENTORE project, this insight reaffirms the need for close cooperation between technical tasks and WPs and the Demo sites. The mentioned barriers need to be kept in mind during development and testing of I-STENTORE technologies, and should be a significant factor in the assessment of the end result. This is a crucial aspect of making sure that developed solutions will actually be usable and have the impact expected of a project of this scale.

5 STORAGE CONCEPTUALISATION AND REGULATORY ASSESSMENT

The goal of this section is to 1) conceptualise energy storage in power sector decarbonisation, 2) to provide an overview of EU level regulation on the integration of energy storage to the power system and 3) to assess the key regulatory barriers to integration in selected Member States (demo countries of the i-STENTORE project) based on a stakeholder survey. The report defines storage as device that can absorb and eject electricity both in-front and behind-the-meter.

5.1 CONCEPTUALISING STORAGE

The decarbonisation of the EU economy by 2050 requires a net zero power system by 2035 (Figure 35). Such a system is based on renewable energy resources, mostly wind and solar (Figure 36). The inherent variability of the power supply and the phase-out of traditional balancing generators (mainly gas and coal power plants) necessitates a fundamental shift in system operations: moving from a world where we forecast load and schedule generation, to a world where increasingly we forecast generation and schedule load.

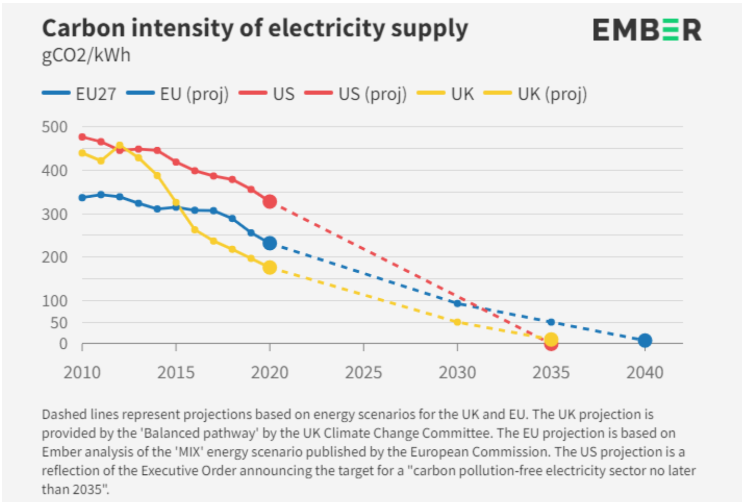

FIGURE 35: CARBON INTENSITY OF ELECTRICITY SUPPLY [153]

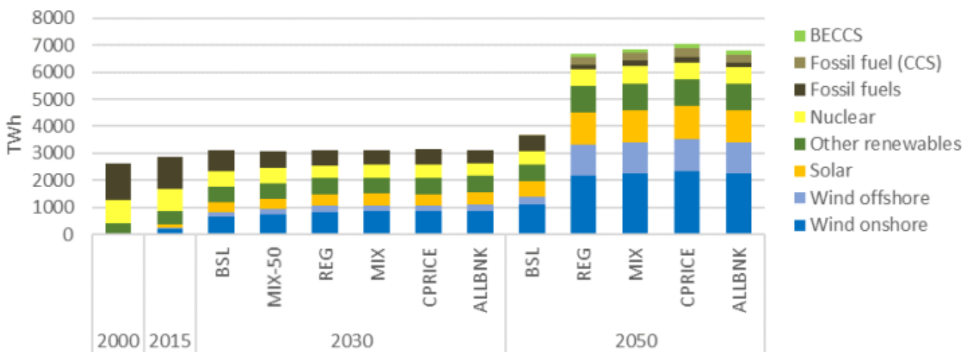

FIGURE 36: ELECTRICITY PRODUCTION SCENARIOS OF THE EUROPEAN COMMISSION [154]

This new modus operandi of the power sector is the implementation of the energy efficiency first (EE1st) principle - being a new cornerstone of EU energy policy. EE1st requires decision makers to consistently consider demand-side resources as alternatives to supply-side resources, including generation and networks, prior to investment decisions. It also requires that those demand-side options be implemented whenever they are more cost-effective than the supply-side solutions [155]. In the power sector this mainly refers to emancipating the flexibility of demand-side resources. In order to equate supply and demand at every second, demand cannot be taken as exogenous but consumers need to be considered as power system resources. Electrification of heat and transport is the fundamental way these energy services will get decarbonised. The cost-efficient integration of these additional loads requires their alignment, together with existing loads, to the generation patters of variable renewable resources.

The increasing share of wind and solar necessitates the ramp-up of flexibility with a sharp increase of daily and weekly flexibility requirement above 70% of RES share in total demand (Figure 37).

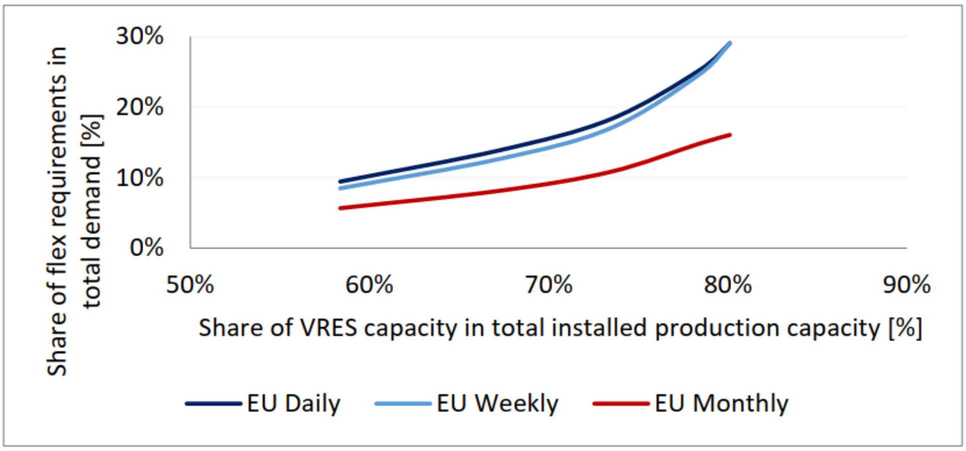

FIGURE 37: SHARE OF DAILY, WEEKLY AND MONTHLY FLEXIBILITY REQUIREMENTS IN TOTAL DEMAND IN RELATION TO INCREASING SHARE OF VRES CAPACITY IN TOTAL INSTALLED PRODUCTION CAPACITY IN THE EU [156]

The future power system will require all available flexibilities: storage is just one of them. Others include flexible generation, demand-side flexibility, smarter and stronger transmission and distribution networks, sector coupling, e.g. RES-based hydrogen production and vehicle-to-grid. As an example, Figure 38 shows the modelled portfolio of flexibility options for the EU, Germany and Italy in 2030. Interconnectors are key flexibility sources, together with the portfolio effect[2], flexible generators and demand-side options ('Others'). They all provide flexibility to the power system, albeit their services are not identical, and their mobilisation might require different regulatory tools. Utility scale batteries or flexible generation can be triggered with undistorted price formation in the wholesale markets and suitable ancillary service products, whereas the smarting of distribution networks requires a targeted regulatory reform delivered by the respective national regulators with regards to how these companies are remunerated. The various flexibility options should always be assessed against alternatives with regards to technical suitability (can it provide the service reliably?) and cost-efficiently (at what cost?). This equally applies to the various storage options as well. Figure 39 shows the LCOE forecast for various storage technologies per application. Battery technologies exhibit the highest probability of lowest LCOS in most applications beyond 2025. Hydrogen is likely to be dominant for seasonal storage.

[2] Diversification means that the contribution of the sum of different technologies may outperform the contribution of the sum of the individual technologies.

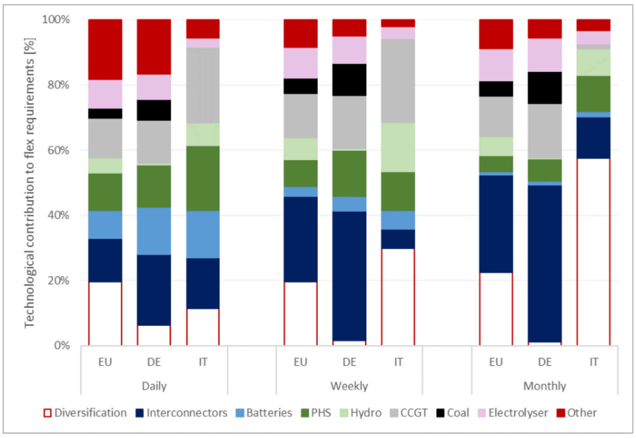

FIGURE 38: TECHNOLOGICAL CONTRIBUTION TO FLEXIBILITY REQUIREMENTS IN THE EU, GERMANY AND ITALY, 2030 [156].

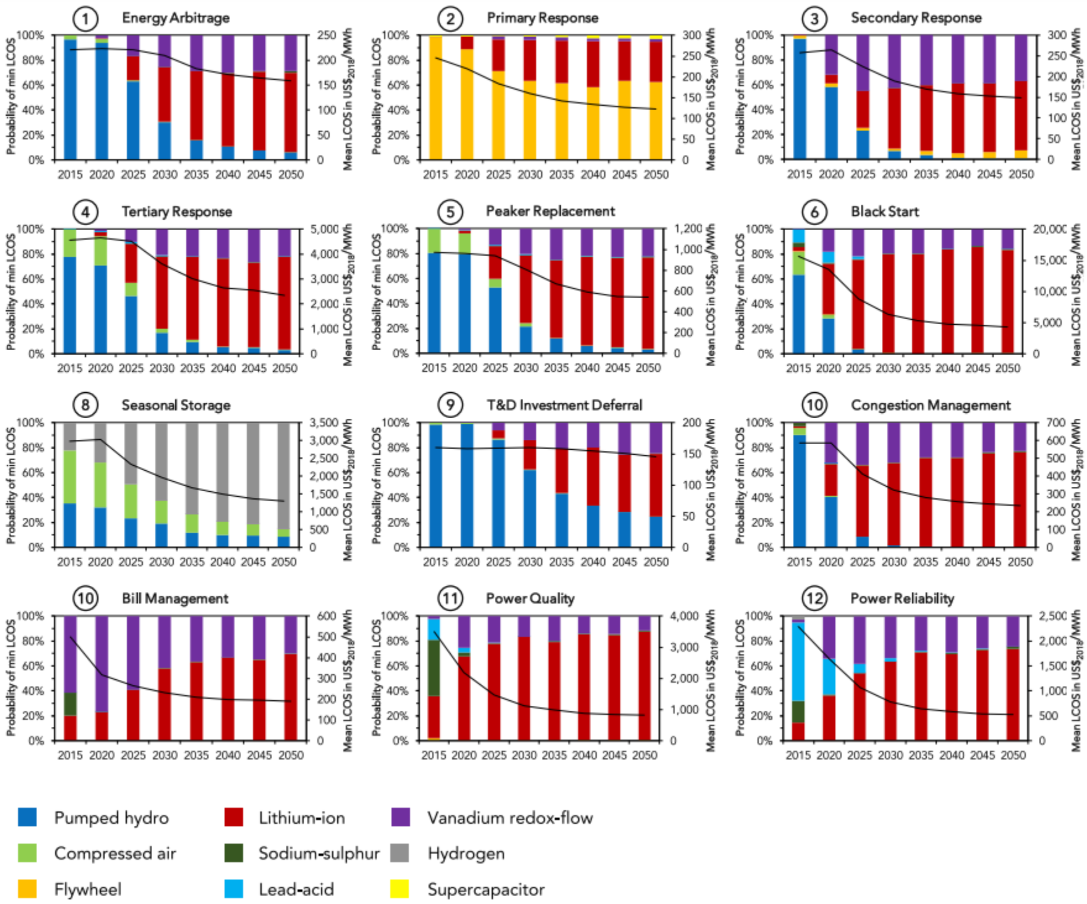

FIGURE 39: LOWEST LCOS PROBABILITIES FOR 9 ELECTRICITY STORAGE TECHNOLOGIES IN 12 APPLICATIONS FROM 2015 TO 2050[3]

[3] Left-hand axis displays probability that a technology will exhibit the lowest LCOS in a specific application. Right-hand axis displays mean LCOS of technology with highest probability for lowest LCOS.

5.2 SYSTEM BENEFITS OF STORAGE

Storage provides various services to the power system [157]–[160]. It is important to note that different storage technologies are more suited to certain system services depending on technology characteristics such as response/ramp up time, duration, power/energy capacity and synchronous inertia capabilities (see Figure 40 for illustration). Service scope depends on the operational mode and physical location as well: whether the storage is coupled with generation (e.g. solar+storage increasingly substituting gas peaker power plants) or whether it is at the transmission/distribution network or behind-the-meter.

Parameters	VRLA	Pumped Hydro	CAES	Flywheels	NMC	NCA	LFP	LTO	NaS	NaNiCl2 (Zebra)	ZBB	VRB
Renewable Shifting	0.8	1.0	1.0	0.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Renewable Smoothing	0.8	0.3	0.3	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.3	0.3
Flex Ramping	0.8	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Ancillary Services	0.5	0.3	0.3	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.3	0.3
T&D Deferral	1.0	1.0	1.0	0.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Reactive Power Management	1.0	0.3	0.3	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.3	0.3
BTM Power Management	1.0	0.0	0.0	0.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

FIGURE 40: EXAMPLE OF SUITABILITY MATRIX FOR DIFFERENT STORAGE APPLICATIONS [159]

General system services provided by storage range from better renewable integration to more reliable system operation and prices (Figure 41 in blue). These services are delivered either to network companies (Grid support and ancillary services), to consumers (Consumer management services) or to the bulk power system (Generation support services).

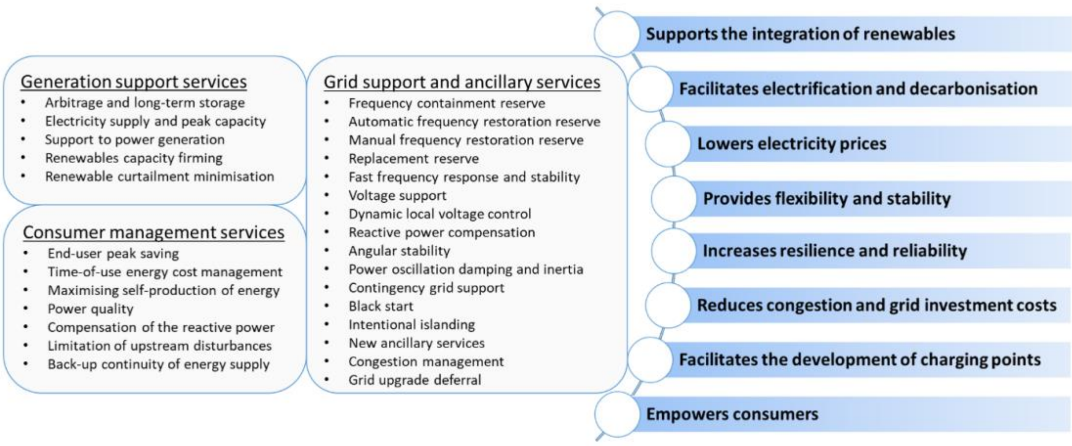

FIGURE 41: ENERGY-STORAGE APPLICATIONS AND ADDED VALUE [158].

5.3 DOES STORAGE REQUIRE PUBLIC SUPPORT?

The key regulatory requirement for the efficient integration of storage to the power system is that all benefits need to be remunerated according to their system value and the various streams of revenue must be stackable. It secures the optimal level of storage investment and provides the revenues to storage owners commensurate with the benefit they create to the power system. Not or undervaluing some services worsens the business case and results in suboptimal storage investment.

Storage owners today serve various markets. Balancing markets (especially frequency containment services) are relatively small in volume but have high prices [157]. Arbitrage becomes increasingly profitable with the increasing overall price levels translating into bigger absolute intraday spreads. As the limited balancing markets get saturated with increasing storage and other flexible capacities getting online, investors need to look for other stable revenue sources such as flexibility offered to network operators for congestion management, and non-frequency ancillary services.

It is not enough to have access to these markets but they need to be conducive for DSF and storage, most importantly:

- power prices have to reflect demand and supply conditions - without any price cap or floor – and to be granular in time and location
- short-term prices need to reflect the value of available reserves (scarcity pricing)
- equal and effective access of demand-side resources and storage to all markets by redesigning rules and products (e.g. bid size as small as 100kW).

This has been underlined by a recent survey where most respondents indicated that "*fair access to technology-neutral competitive markets across the whole EU, including remuneration of energy system services that are currently not valued, would be the most desired way to support energy storage*" [157].

Behind-the-meter storage is an essential part of the flexibility puzzle. It is unique, as investment to these assets is made by consumers and most often not primarily driven by their power system value. People buy EVs for various reasons, including efficiency, lower lifetime cost but also environmental values [161]. They often install small-scale batteries for resiliency and self-sufficiency in case of grid failure or to avoid high retail tariffs in evening peaks. EVs is estimated to be adding 45GW of battery capacity to the European grid annually by 2030 [162]. This is a vast resource that is already purchased and integrated to the grid by consumers and being aggregated can provide all the system benefits utility scale storages can. The regulatory tasks in their case go beyond fair market integration and includes the design of retail energy and network tariff incentivising the use of this flexibility and also supporting and requiring (e.g. by building codes) charging infrastructure to develop.

Even if all values are remunerated and markets deliver price signals on these values, the role of storage in future power systems depends on the evolution of its technology cost vis-à-vis other flexibility options (supply of flexibility) and the speed of substituting traditional flexible generators with intermittent renewables (demand for flexibility).

Flexibility alternatives need to be evaluated from the social/system point of view but it is the private perspective that defines the business case. Under perfect markets these two would equal. In real life, if the revenue streams to the owner do not cover the cost of the storage project but system benefits outweigh the cost then intervention is justified. Public support accelerates the deployment of storage assets but it needs to be designed in a technology-neutral way (e.g. storage versus DSF), and not distorting short term market signals. Such support does not substitute for improving markets so that revenues are aligned with value created.

Specific tools could include contracts-for-difference (CfD), 24/7 clean power purchase agreements; investment support or capacity payment from existing CRMs. The form of support is part of the discussion on the ongoing reform of the European electricity market design (see later). CRMs are limiting price formation on short-term markets and are hence detrimental for DSF and storage. CRMs excluding these zero carbon technologies would be even worse. Most importantly, support should not be tilted towards utility scale storage at the expense of existing and forthcoming consumer flexibilities, including storage.

5.4 DOES STORAGE REQUIRE SPECIAL REGULATORY TREATMENT?

Technically, storage is an asset that performs both the function of a generator (injection to the grid) and a consumer (withdrawal from the grid). Does this feature justify a dedicated regulatory treatment of storage? The EC recommends that "*Member States take into account the double role (generator-consumer) of energy storage when defining the applicable regulatory framework and procedures, in particular when implementing the Union legislation concerning the electricity market, in order to remove existing barriers. This includes preventing double taxation and facilitating permit-granting procedures. National regulatory authorities should also consider such a role when setting network charges and tariff schemes, in compliance with Union legislation*" [163].

The adjacent SWD ask for a regulatory framework that *"(i) avoid(s) existing barriers; and (ii) maximise(s) the added value that energy storage can bring to the energy system"* [157]. These principles are not intrinsic to storage but need to be applied to all flexibility options in general. The entry barriers are specific to demand-side resources (including storage) as market rules has been traditionally designed for large scale generation.

The regulatory questions specific to storage are limited to:

- Double taxation: by default, storage pays taxes and levies based on kWh transferred to/from the grid twice (at withdrawal and injection)
- Network tariff: is there a need for a special network tariff (concession) for storage?

5.4.1 Double taxation

Charging kWh-based taxes and levies twice for every storage cycle is not justifiable from a system perspective as consumption or production serve as a proxy to allocate certain socialised cost of the energy system among producers and consumers according to their size. This has been recognised in the Energy Taxation Directive proposed under the Clean Energy Package and in the 2023 Recommendations. Several options are discussed:

- Taxing only final consumption would mean making storage fully exempt from this contribution. Full exemption is not fair plus it would provide a competitive advantage over DSF that would pay the same amount when shifting load from one period to another.
- Another option is to levy only on technical losses (difference between withdrawn and injected electricity). That would require some contribution from storage systems (albeit still less than DSF) to the overall system cost embodied in the taxes/levies and also incentivise for higher efficiency storage options.

5.4.2 Network tariffs

Similar to double taxation, double charging of network tariffs deteriorates the business case for storage [164]. From a system perspective, storage – just like any other network users- needs to cover the cost its use causes to the network at a certain time and location. Defining efficient and fair network tariffs for storage, hence, is more complicated depending on whether producer lays as well or only consumers, to what extent the network tariff is cost reflective, and volumetric or fixed (mostly based on some definition of capacity). Tariff practice in Europe varies.

	Subject to withdrawal charge	**NOT subject to withdrawal charge**
Subject to injection charge	AT, BE (FLA and WAL), DK, FI, FR[90], IE, NO, RO[91], SK, SE[92]	
NOT subject to injection charge	BE (BRU), BG[93], HR, CZ, FR[94], DE, GR, HU, IE, LT, LU, MT[95], NL, PL, PT	CY, IT, SI, ES

Note: No storage facilities are connected to the transmission grid in: CY, EE, LV, LU, RO, SE; No storage facilities are connected to the distribution grid in: BG, CY, EE, GR, LV, LT, LU; Some countries appear multiple times in the Figure (e.g. due to differences between transmission and distribution); Negative injection charge is not accounted for the Figure.

TABLE 23 : APPLICATION OF NETWORK CHARGES TO STORAGE FACILITIES [165]

ACER recommends that:

- If a network user both withdraws from and injects into the grid, both network uses should be considered when setting the tariffs, by properly taking into account the potential cost-offsetting effect and the overall cost-impact to the network.
- In this regard, where volumetric charges apply, net-metering (i.e. payment based on the net balance of injected and withdrawn energy) should be avoided as it is not cost-reflective and shifts costs to those users who only inject into or only withdraw from the grid [165].

The Recommendations remain rather vague on network tariffs: “National regulatory authorities should also consider such a role when setting network charges and tariff schemes, in compliance with Union legislation” [163].

Further EU rules and regulation relevant for the integration of storage are discussed in the next section.

5.5 EU REGULATION

There is no dedicated energy storage legislation at the European level.[4] All the major recent policy documents reaffirm the role of storage, including the Green Deal, the RePowerEU, the System Integration Strategy, and the Green Deal Industrial Plan. Several pieces of legislation include provisions relevant to storage (Table 25).[5] The Recommendation on Storage published recently is a policy and regulatory guidance for future EU legislations with storage relevance but also for member states in implementing EU rules [163].

1.	Member States take into account the double role (generator-consumer) of energy storage when defining the applicable regulatory framework and procedures (…). This includes **preventing double taxation** and facilitating permit-granting procedures. National regulatory authorities should also consider such a role **when setting network charges** and tariff schemes, in compliance with Union legislation.
2.	Member States identify the **flexibility needs** of their energy systems in the short, medium and long term, and in their updates of the NCEPs (…) to cost effectively promote the deployment of energy storage, both utility-scale and behind-the-meter storage, demand response and flexibility.
3.	(…) National regulatory authorities, (should) ensure that energy system operators further assess the flexibility needs of their energy systems **when planning transmission and distribution networks**, including the potential of energy storage (short- and long-term duration) and whether energy storage can be a more cost effective **alternative to grid investments**. (…) and when assessing their connection capacity (e.g. considering flexible connection contracts) and operating the system.
4.	Member States identify potential financing gaps for short-, medium- and long-term energy storage, including behind-the-meter (thermal and using electricity) and other flexibility instruments.
5.	Member States explore whether energy storage services are **sufficiently remunerated**, and whether operators can **add up the remuneration of several services**.
6.	Member States to consider **competitive bidding processes** if necessary to reach a sufficient level of deployment of flexibility sources to achieve transparent security of supply and environmental objectives, in line with State Aid rules. Potential improvements should be explored in the **design of capacity mechanisms** to facilitate the participation of flexibility sources including energy storage (…).
7.	Member States identify any specific actions, regulatory and non-regulatory, necessary **to remove barriers to the deployment of demand response and behind-the-meter storage** (…).
8.	Member States accelerate the deployment of storage facilities and other flexibility tools **in islands, remote areas.**

[4] EU battery legislation focuses mainly on the circular economy aspects of batteries manufacturing.
[5] It is important to note that several are still at various stages of co-legislation and not the final version in effect. In these cases, we used the most recent version available in June 2023.

9.	Member States and national regulatory authorities publish **detailed data on network congestion, renewable energy curtailment, market prices, renewable energy and greenhouse gas emission content in real time**, (…), to facilitate investment decisions on new energy storage facilities.
10.	Member States continue to **support research and innovation** in energy storage, **in particular long-term energy storage** and storage solutions coupling electricity with other energy carriers, and to optimise existing solutions (…).

TABLE 24 : SUMMARY OF THE RECOMMENDATIONS ON STORAGE

Name	Status	Relevance	Reference in Recommendations
Energy Taxation Directive	Proposal	Double taxation	1
Energy Performance of Buildings Directive	Proposal	Rules on EV charging infrastructure	7
Renewable Energy Directive	Proposal	, Bidirectional charging, data access and infrastructure planning	3, 7
Network Code on DSF	Proposal	EU minimum rules on market access of DSF	5,6,7,8
Alternative Fuel Infrastructure Regulation	Proposal	Smart charging-ready charging points	7
Energy Efficiency Directive	Proposal	Energy efficiency provisions extended to DSF (including storage)	7
Electricity Directive and Regulation (2019)	In force	Network tariffs, network planning and transparency, remuneration, deployment support, active consumers	1, 3, 5, 6, 7, 8, 9
Net-zero Industry Act	Proposal		4

TABLE 25 : EU LEGISLATION RELEVANT FOR ENERGY STORAGE MARKET INTEGRATION

5.5.1 Energy taxation directive

The proposal for the Energy Taxation Directive relieves storage from double taxation: "*As regards electricity, recent and future developments of storage technologies would require that electricity storage facilities and transformers of electricity could be considered redistributors when they supply electricity in order to avoid the risk of double taxation (see Article 22(4) (2nd subpar.))*." (Detailed explanation of the specific provisions of the proposal, Item 12) [166].

5.5.2 Energy Performance of Buildings Directive

The Directive is under revision at the time of drafting but offers an important opportunity to accelerate residential and workplace EV charging. The proposal of the European Commission includes requirements for new buildings and those undergoing major renovation[6]:

- to have certain number of recharging points per parking place, depending on the function of the building (residential, non-residential) and the size;
- to equip all parking places with pre-cabling. This allows for quicker and cheaper installation of recharging points later on; and
- to make sure that recharging points are capable of smart charging and bidirectional charging, and that they are operated based on non-proprietary and non-discriminatory communication protocols and standards (Article 12).

In addition, the Directive introduces a common Union scheme for rating the smart readiness of buildings, based on an assessment of the capabilities of a building or building unit to adapt its operation to the needs of the occupant and the grid and to improve its energy efficiency and overall performance. The label is an information tool that would express how much the building (including behind-the-meter storage) can be integrated to the power system. The methodology is yet to be developed [167].

5.5.3 Renewable Energy Directive

The final RED proposal (outcome of the negotiation between the European Council and the European Parliament) includes several storage relevant provisions aiming at a more efficient integration of renewables by requiring from member states:

- to establish a framework and extend several planning provisions for renewables to facilitate the uptake of co-located energy storage projects ('a project encompassing an energy storage facility and a facility producing renewable energy connected behind the same grid access point' (Article 1);
- to consider a range of national measures, including "smart and bidirectional charging, other flexibility services such as demand response" to mainstream renewable energy in buildings (Article 15a). As EV recharging points are "highly relevant to energy system integration, therefore smart and where appropriate bidirectional recharging functionalities need to be ensured" (Article 17a);
- to ensure that "new and replaced non–publicly accessible normal power recharging points installed in their territory (…) can support smart charging functionalities and (…) bidirectional charging functionalities" (Article 20a);

[6] The European Council and the European Parliament prepared their positions as well for the upcoming trialogue: European Parliament's consolidated position: Amendments adopted by the European Parliament on 14 March 2023 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast). https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.pdf; EU Council general approach. Council of the European Union. Proposal on energy performance of buildings https://data.consilium.europa.eu/doc/document/ST-13280-2022-INIT/en/pdf and final amendments https://data.consilium.europa.eu/doc/document/ST-13280-2022-COR-1/en/pdf.

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- to ensure that battery and EV manufacturers make available real time data on "battery state of health, battery state of charge, battery power set point, battery capacity, and as well as where appropriate the location of electric vehicles" to battery owners and users and third-parties based on consent (Article 20a);
- to designate dedicated areas for grid and storage development necessary for renewable integration (Article 15e) [168].

This final text omits the proposal of the Parliament that would have required MSs to set a minimum indicative national target for demand-side flexibility and set an indicative target for storage technologies [169].

5.5.4 Network Code on DSF

ENTSO-E and the EU DSO Entity are currently developing a new network code for demand response. It is due to be submitted to ACER in February 2024, also including the outcome of the current reform of the EU electricity market design to be embodied in the amendments of the Electricity Directive and Regulation of 2019. The network code aims at enabling market access for demand response, including load, storage and distributed generation as well at facilitating the market-based procurement of services by distribution and transmission system operators. It will be applicable to all Member States.

5.5.5 Alternative Fuel Infrastructure Regulation

The AFIR facilitates energy storage in EV batteries via its requirement of "smart charging capable" charging points, meaning all new charging points will have to be responsive to external signals from the grid which incentivizes use of EV batteries for temporary energy storage.

5.5.6 Energy Efficiency Directive

The proposed EED reaffirms the benefits of demand-side flexibility (including storage) and calls for the application of the energy efficiency principle (Preamble 14). It prioritises the removal of barriers in the energy markets that impede efficiency in the supply, transmission, storage and use of energy (Art 1(1)). Behind-the-meter energy storage options need to be included on energy audits and assistance for households and SMEs on energy renovations, electrification of heating (Art 21(2)). Energy performance contracting by public bodies gets expanded to include demand response and storage as well (Art 27(4)). Annex XII reconfirms the need to provide full access of demand-side flexibility (including storage) to organised markets.

5.5.7 Electricity Directive and Regulation Electricity Directive and Regulation (2019)

The Electricity Directive and the adjacent Regulation adopted in 2019 together provide for the regulatory framework for the integration of demand-side resources, including storage. The most important provisions of the Directive are:

- Definition of storage (Article 2(59))
- Storage belongs to the competitive segment of the power market and hence network companies are not allowed to own them, except when the tender for flexibility service failed (assessed by the regulator) and the network company cannot operate the grid without it or storage is a fully integrated component of the network (Article 36 and 54).[7] This latter derogation has been used by three German TSOs to add batteries to boost the utilisation rate of transmission lines alongside the N-1 redundancy that must be built into any network. The batteries free up capacity by providing for contingency,[8]
- The rights of active consumers owning storage: grid connection, no double charging, right to offering system services (Article 15(5)).
- Prohibition of double taxation (just as in the 2023 Storage Recommendation)
- Regulatory framework for DSOs to use flexibility services, including storage (Article 32(1)) and prepare network development plans including the use of DSF and storage. (Article 32(3)).
- TSOs have to include DSF/storage in procuring balancing services (Article 40).
- TSOs cannot refuse grid connection of new generation and storage on the ground that it results in possible future congestion in distant parts of the transmission system (Article 42).
- The TYNDPs prepared by the TSOs have to take fully account of DSF/storage (Article 52).

The Regulation focuses on the integration of DSF/storage to the power markets by requiring

- market rules to provide adequate investment incentives for and enable the efficient dispatch of generation, DSF and storage and shall facilitate competition (Article 3).
- non-discriminatory access to balancing markets (Article 6), day-ahead and intraday markets with a minimum bid size of 500kW or less (Article 8), redispatch (Article 13),
- network tariffs not discriminating against energy storage and aggregation and enabling the DSF/storage and self-generation by eliminating regulatory distortions (Article 18).
- any capacity mechanism being open to DSF/storage (Article 22).

5.5.7.1 Current EMD reform

[7] A 'fully integrated network components' means network components that are integrated in the transmission or distribution system, including storage facilities, and that are used for the sole purpose of ensuring a secure and reliable operation of the transmission or distribution system, and not for balancing or congestion management; ED Article 2(51).
[8] https://www.energy-storage.news/frances-grid-battery-experiments-take-aim-at-creating-market-fit-for-carbon-neutrality/

The European Commission launched an expedited reform of the electricity market design as a response to the energy price crisis triggered by the war Ukraine [170]. Although there are no storage-specific elements in the Commission proposal amending the Electricity Directive and Regulation, they include several provisions relevant for the enhancement of power system flexibility.

- Every 2 years, NRAs must assess and report on flexibility needs for a period of 5 years: the need for flexibility to integrate RES-E and the potential for non-fossil flexibility such as DSR and storage. NRAs to submit reports to ACER, which will report and issue recommendations. Members States to indicate objectives for DSR and storage, based on NRAs' reports (Article 19c and 19d).
- TSOs and DSOs have to publish and update information on the grid capacity available in their areas of operation would inform investors on how they can connect to the grid quickly (Recital 41).
- NRAs shall introduce performance targets to provide incentives to network companies to "increase efficiencies in their networks, including through energy efficiency, the use of flexibility services and the development of smart grids and intelligent metering systems and (…) *shall consider both capital and operational expenditure to provide appropriate incentives*. (Article 18)"
- Member States with a CRM must consider the promotion of non-fossil flexibility such as DSR and storage, by amending the CRM. If there is no CRM, Member States may apply flexibility support schemes consisting of payments for capacity for flexibility. Flexibility support schemes must:
- not go beyond what is necessary to address identified flexibility needs;
- be limited to new investments;
- not involve starting fossil fuel-based generation behind the metering point;
- select capacity providers by an open, transparent, competitive, non-discriminatory and cost-effective process;
- not distort markets;
- incentivise integration;
- set out minimum levels of participation in the market in terms of activated energy;
- apply appropriate penalties to capacity providers that do not respect minimum levels of participation;

  be open to cross-border participation (Articles 19e, 19f).
- TSOs may procure peak shaving products to reduce demand in peak hours (Article 7a). It is important to note that the peak shaving product is limited to demand response.
- The size of day-ahead and intraday product must be 100 kw or less (Article 8).

5.5.8 Net-zero Industry Act

The aim of this proposal is to ensure the EU can domestically produce at least 40% of the technologies it deems "strategic" to achieve its goal of reducing emissions to net zero by 2050 to reduce reliance on non-EU sources [168]. "Strategic technologies" include wind, solar, batteries and electrolysers would benefit from quicker permitting procedures (capped at 18 months for storage), priority in public procurement and looser state aid EU oversight.

5.6 FINAL REMARKS

Storage system are vital element of the future power systems that is built of variable renewable production and flexibility. Storage is one source of flexibility and as such its deployment needs to be assessed vis-a-vis other options such as demand-side or generation flexibility. Markets via effective pricing can provide the needed incentives to utilise the type of flexibility when and where it is beneficial from the system perspective. Technologically-neutral markets are the key tenet of a low cost energy transition. The main storage specific issues are double taxation and network tariffs. Both arise from the fact that storages are bidirectional. Double taxation is prohibited but there is no clear guidance on how to design appropriate network tariffs.
There is no specific EU legislation on storage but the recent EU storage strategy lists the key directions MS need to consider. The Electricity Directive and Regulation of 2019 provide the framework for the integration of storage and demand-side resources in power markets and systems. The implementation of these rules is moving forward but in an uneven pace across the MSs. There are numerous other pieces of upcoming legislation, including the ongoing reform of the European single electricity market that have an impact on storage deployment and integration. These are likely to provide further guidance and requirements for mobilising flexibility in the power systems.

The results of the barriers survey (Chapter 4) make it clear that regulatory barriers for the development of storage technologies and strategies exists in all five countries, and are being addressed with quite different degrees of success. The fast pace of technology and business development on the ground are a main cause for the existing issues with regulation: the organizational frameworks of markets and network operations cannot keep up with development of technologies and stakeholder requirements, and as a result many existing rule sets and policies are either ignore the reality of new and flexible stakeholders, or they are new and not yet fully refined to everyday circumstances. However, developments can be observed that incrementally improve on these problems.
In addition to the individual barriers themselves, their inconsistency across different countries raises replicability concerns for multi-nation projects such as I-STENTORE. Developing a solution flexible enough to take into account this diverse landscape of regulations and customs is a challenge, especially with the aforementioned ongoing changes and volatility in the situation. This insight reaffirms the need for close cooperation between technical tasks and WPs and the Demo sites. The mentioned barriers need to be kept in mind during development and testing of I-STENTORE technologies and should be a significant factor in the assessment of the end result. This is a crucial aspect of making sure that developed solutions will actually be usable and have the impact expected of a project of this scale.

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6 USE CASES

6.1 AGRI-PV FARM WITH ENERGY STORAGE CAPABILITIES BASED ON HYDROGEN AND BESS TECHNOLOGIES (LUXEMBOURG)

Scope	An agri-photovoltaic (APV) plant and windpower productions are combined with high-performance energy processes provided by a hybrid energy storage system, composed by utility-scale Li-battery and green hydrogen, including the optimization of renewable energy use and the supply of ancillary and flexibility services to the grid operator to improve the grid reliability and power quality.
Objective(s)	• Demonstrate the interest of an innovative energy storage combination in an APV plant to optimize energy use and to provide grid support services to the system operator, reducing the APV energy related costs. • Demonstrate that energy storage systems not only improve the energy performance of the APV plant, but also other processes related to the plant's crops, microclimate, and biodiversity. • Improve the grid reliability and power quality by providing flexibility and ancillary services to the grid operator. • Demonstrate how storage systems can improve the APV plant business case. • Demonstrate an open and secure interaction of all actors due to the energy management platform dedicated to the APV plant.

Actor name	**The roles of the actor**
Luxembourg Institute of Science and Technology (LIST)	• Demonstrate and validate the performance of a digital platform for energy and services management based in a high-precision hierarchical control model to dynamically manage multiple active units distributed over the network, using innovative virtual shafts controllers which accuracy is guaranteed by a satellite synchronization system of multiple synchro-phasor units. • Collaborate in the definition of new in business cases for Agri-photovoltaic farms supported by energy storage systems. • Integrate the real-time signals and data generated from the energy processes of the Agri-photovoltaic plant into the Luxembourg nationwide digital twin (NWDT)
Green Power Storage Solutions S.A. (GPSS)	• Exploitation of the energy- and non-energy-related processes of the agri-photovoltaic plant. • Test new business models applied to Agri-photovoltaic farm.
Studio elektronike Rjieka (STER)	• Demonstrate the performance of phasor measurements units (PMUs) integration with the control system supporting an effective interaction between the APV plant operator and the grid operator for the provision of ancillary services.
CEN Solutions (CEN)	• Demonstrate the performance of a utility scale Li-Ion BESS in a hybrid energy storage system associated to the processes of an Agri-Photovoltaic plant.

Assumptions
Regulatory assumptions:
Storage systems are allowed to provide flexibility and grid ancillary services by the local authorities. Storage assets can normally operate on the wholesale markets.
Technical and other assumptions:
All developed and tested digital solutions are compatible and able to be integrated into an interoperable environment.
The installation permits for the physical systems and its connection to the grid are timely granted.

Narrative of Use Case
The hybrid energy storage system projected for demonstration in Luxembourg combines different storage technologies with a 3 MWp agri-photovoltaic power (APV) plant and a 4,2 MW wind-generator with the purpose of increasing the plant's energy flexibility, optimizing the interaction of the renewable energy generation with the electric grid by providing ancillary and flexibility services to the grid operator. The energy processes of the APV plant will be correlated with other agricultural, biodiversity and microclimatic processes, which will result in numerical models to simulate all the pieces and interactions of the plant under generic operating conditions, optimizing the energy generation and exploiting the system according to multi-objective principles, taking into account the potential degrees of freedom offered by energy storage systems. The planed storage mechanisms are a utility-scale Li-Ion BESS, 1MW/1MWh, and a local green hydrogen storage system, composed by a 3MW electrolyser and respective storage tank. The produced and stored hydrogen will be used together with other mechanisms in a multi-energy vehicle station (electric supercharging and hydrogen fuelling). Moreover, it is also planned to dilute a fraction of the produced green hydrogen in the natural gas production of a local biogas plant, increasing the fuel volume throughput. The utility-scale BESS will allow to optimize the bi-directional power flows of the APV plant, resulting in increased flexibility of its electrical performance and the energy exchanges with the power grid minimizing the energy related costs of the plant and maximizing the profit on trading energy surpluses. This BESS, with grid-forming functionalities will be installed together with the multi-energy station interacting with other energy assets in the farm and will offer high-quality ancillary and flexibility services to the distribution system operator. In addition to the conventional flexibility services, mainly based on quasi-static modulation of plant power flows in terms of amplitude regulation, time shifting and limitation of rate-of-change-of-power (ROCOP), the BESS will offer dynamic ancillary services aimed at improving grid stability, robustness, and resilience. These services are based on implementing innovative virtual shafts controllers patented by LIST. In this way, the plant's BESS will not only react dynamically to the evolution of the electrical magnitudes at the point of common coupling with the grid, but it will also react instantaneously to the evolution of the signals at certain significant grid nodes in its area of influence.

6.2 COOPERATIVE MODULAR MULTI HYBRID ENERGY STORAGE SYSTEM BASED ON HYBRID SUPERCAP/LI-NMC BATTERIES FOR SMART DC MGS OF E-MOBILITY SERVICE (ITALY)

Scope	Creation of Multi-Charger Hub for EV-Mobility Service. The Hub uses Innovative Storage Systems based on Hybrid Supercapacitor/NMC battery technologies and AC/DC Smart MicroGrid architecture for integrating PV source.

	The Multi-Charger Hub consists of different charging slots integrated with a PV source and distributed Energy Storage Systems (ESSs): • Quick-AC Charger • Ultra-Fast DC Charger • Portable Swappable Battery Charger on Demand
Objective(s)	Demonstrate that use of Stationary Hybrid Energy Storage for improvement of EV Ultra-Fast Charging performance in terms of EV charge time and lower power grid impact, promoting the concept of “We Bring Energy to Your Vehicle Right, Where and When its Needed” using Portable Swappable Battery Charger for reducing range anxiety. Improve PV grid penetration and sharing of extra-stored energy from stationary hybrid storage plant and Mobile Charger for EV mobility service, as well as the Battery Second Life. Thanks to EV Hub, related sharing EV cars and Portable Battery Charge we’ll promote EV mobility on Amalfi Coast and Cilento Coast.

Assumptions
Regulatory assumptions:
Grid integration with V2G capability of AC/DC Smart MicroGrid and reduce the energy absorption peak of Ultra-Fast EV Charger
Technical and other assumptions:
• exchange energy with V2G protocol between EV Charger and EV cars. • HESS allows to reduce the stress of NMC battery in terms of maximum repetitive C-rate and ensuring the EV Ultra-Fast Charging performance. • Test second life battery on Portable Charging Stations. • Generate data to monitor FV production and V2G bidirectional energy exchange from Micro grid to Main Grid. • Collect EV charging data to allow on Demand Service

Narrative of Use Case
This use case describes an EV charging Hub with FV roof for sharing electric cars with leading-edge technology such as hybrid energy storage system that powers an engineered Ultra-fast charging station. Additionally, we’ll include experimentation of future V2G standard that allows the bi-directional charge of EV car, in case of energy peak on the main Grid it can drain the power previously stored in the EV’s battery and send back the energy to stabilize the Grid. Above all this project will try to introduce electric cars on Amalfi Coast and Cilento Coast to encourage green mobility for tourism purpose.

6.3 MOLTEN GLASS THERMAL STORAGE FOR AN INCREASED UPTAKE OF RENEWABLE ELECTRIC ENERGY (SLOVENIA)

Scope	Aligning the glass melting process, i.e. coordinated manipulation of electric boosting at uncompromised glass batch quality, with the availability of RES and opening-up glass manufacturing to provide ancillary services
Objective(s)	• Decreased carbon footprint of glass melting process by higher uptake of RES; • Higher utilization of PV power plant and lower energy costs; • Higher overall share of RES in fed-in energy mix for glass melting; • Resilience to energy supply disruptions of glass manufacturing process (higher energy autarky); • Increasing the resilience and security of energy systems by opening up the glass manufacturing process to provide auxiliary services.

Actor name	The roles of the actor
Steklarna Hrastnik (HRAS)	End-user of solution (packing glass manufacturer) and owner of facilities. The main goal/benefit is to lower the carbon footprint of glass melting and increased self-use of RES.
Comsensus (COMS)	Enhancing flexibility platform for Improved RES Utilization and Supply Disruption Resilience.
Network operators (DSOs, TSOs) / Aggregators	Auxiliary services for a higher uptake of RES

Assumptions
Regulatory assumptions:
Storage systems are well accepted and supported for the provision of various flexibility services. Besides system services, storage assets can normally operate on the wholesale markets.
Technical and other assumptions:
The hybrid furnace can be upgraded to molten glass storage without negatively affecting the glass batch quality or furnace refractory materials (lifetime).
Historical weather data is available for the location
Operational historical data is available for all assets

Narrative of Use Case
The proposed innovative energy storage system is designed to balance the glass melting process with the availability of local and geo-independent RES for a higher uptake of the latter, thereby simultaneously achieving higher carbon neutrality of glass manufacturing and improved grid stability. For the proposed demo case, we plan to couple the aforementioned hybrid regenerative furnace with a 521 kWp PV power plant located on the roof of the production facility that houses the furnace. The aim is to use molten glass within the furnace as an energy storage unit when surplus energy is available from the PV plant. Particularly, the glass melt will be overheated by up to 35 K by electrodes (boosting) when the electricity generated by the PV system needs to be fully utilized by the furnace. This thermal storage capacity is estimated to be approximately 3 MWh. In order to achieve even higher carbon neutrality, the proposed storage system can also be used to store the surplus energy from Geo-independent RES. For this purpose, the system must include a predictive control system for the hybrid furnace, as electric boosting manipulation must be properly coordinated not to negatively affect the glass batch quality or furnace refractory materials (lifetime). The proposed energy storage

system can also be easily extended for the provision of auxiliary services to the power grid. Namely, SH already offers ancillary services to the TSO at the subject business unit location with its gensets (~0.8 MW regulation flexibility).

6.4 VIRTUAL ENERGY STORAGE SYSTEM FOR RENEWABLE ENERGY INTEGRATION (SPAIN)

Scope	This demo will coordinate two energy storage systems and a hydropower plant to behave as a single Virtual Energy Storage System (VESS) through a digital platform. These three assets will coordinate their operation to provide storage services to two renewable power plants and to the DSO.
Objective(s)	- Optimizing the storage services offered by combining the best characteristics of each of the technologies that make up the VESS. - Reducing the levelized cost of storage (LOCS) of the aggregated storage system. - Improving the business case for renewable plants linked to the VESS. - Increasing the penetration of renewable energy in the grid area supported by the VESS. - Improving the behaviour of the electrical grid through the dynamic and coordinated response of the storage stations that constitute the VESS. - Demonstrating how multiple actors (VESS operator, renewable plant operators, distribution system operator, etc.) can interact in an open, secure and efficient way through the VESS digital operation and control platform. - Demonstrating how the VESS digital management platform can properly interact with other data spaces to improve the overall system performance.

Actor Name	**The roles of the actor**
Renewable plants owners	Optimize production in the Renewable Plants by monitoring and controlling ESS. Improve the incomes of the production thanks to arbitrage. Test demo-capabilities for the offer balancing services to the TSO Test demo capabilities for the participation in traditional energy markets using energy arbitrage as optimizing vector
BESS owner	Test demo-capabilities for the offer balancing services to the TSO

	Test demo capabilities for the participation in traditional energy markets using energy arbitrage as optimizing vector	
DSO	Voltage Regulation by the Activation of Flexibility Services Congestion Management through Flexibility Services	

Assumptions
Regulatory assumptions:
• The local regulatory framework allows the system operator to install and operate storage devices
• The local regulatory framework allows DSOs to operate in flexibility markets
Technical and other assumptions:
• Proper connection of batteries in their corresponding substations
• Provision of grid signals and measurements from the grid operator SCADA
• Provision of data series for optimization purposes (PV forecasting, demand forecasting, hydro scheduling, predicted services requirements, energy and service prices,)
• BESS commissioning by the system operator after FAT and SAT
• Expert operation of the BESS from the system operator
• All the assets are connected to the same grid so the operation of the assets contributes to the general behaviour of the network.

Narrative of Use Case

The VESS to be deployed in Spain represents an ambitious scenario with the coordinated operation and dynamic control of multiple energy storage systems providing services to two associated renewable power plants and reacting to the orders of a DSO thanks to the use of innovative digital control, operation, and management systems. This demonstrator goes beyond optimizing energy storage and uses schemes to maximize/minimize a given collective objective. In this demonstrator, as all the VESS assets are connected in the same area of the grid, operated by MECSA, they will respond coherently and automatically to potential contingencies that may occur in the grid, being the response dynamics and limits for each VESS' asset parameterized by the DSO. In this demonstrator, all the generation plants associated to the VESS are operated by MECSA, which acts as both an ESCO and as a DSO. This allows for assessing multiple use cases without the need of coordinating multiple players. The operation and management tools shall combine multiple objectives in the design of optimized operation schedules, addressing both individual generation objectives set by renewable plant operators and global objectives for providing grid support services to the DSO. Such high-level management will be performed by means of cloud-based optimization algorithms and solvers. The VESS management system will be operated from user-friendly interfaces and APIS, ensuring simple, secure and transparent interaction of all actors in the functional chain (VESS operator, grid operator, plant operators, etc.) and interoperability with other information systems (grid SCADA, markets, meteorological systems, etc.). Use Cases: 1. Voltage Regulation by the Activation of Flexibility Services Addressing how the activation of Flexibility Assets integrated within the same grid can offer services to the DSO when Voltage Regulation is needed. 2. Congestion Management through Flexibility Services Addressing how the activation of Flexibility Assets integrated within the same grid can offer services to the DSO when congestion management is planned to be needed. 3. Test demo-capabilities for the offer balancing services to the TSO The demo-capabilities for balancing services will be assessed. It will be studied how the different assets in the demo can or cannot participate in the different markets regarding balancing services. 4. Test demo capabilities for the participation in traditional energy markets using energy arbitrage as optimizing vector Addressing through the optimization architecture proposed in the demo how the integration of renewable energy can operate with the cost-reducing effect of different market prices (daily, intradaily). There will be an energy arbitrage tool that will allow the generator to maximize its benefits thanks to the hybridization of technologies. 5. Increase the maximum grid capacity in terms of renewable energy integration It will be addressed how the integration of a VESS System can contribute to the increase or decrease of grid capacity for new renewable energy generators.

6.5 HYBRID ENERGY STORAGE INTEGRATION: SYNCHRONOUS CONDENSERS, PUMPED HYDRO, LI-ION BATTERY AND VRFB FOR MULTIPLE SERVICES PROVISION AND INCREASED RES INTEGRATION IN ISOLATED POWER GRIDS, MADEIRA ISLAND – PORTUGAL (USE CASE PT1)

Scope	Use a hybrid ESS (Li-ion battery, VRFB, pumped hydro and synchronous condensers) to increase the robustness of the Madeira island power system and facilitate the safe

	integration of more renewable generation, while maximising the lifetime of the hybrid storage system components. Adapt the dispatch rules of the generation system to eliminate the requirement of always having in operation a minimum number of thermal groups for security reasons.
Objective(s)	Perform the economic dispatch of the Madeira Island generation system (having a hybrid ESS for the provision of multiple regulation services) using a security constrained multi-temporal OPF. The goals are: • Minimise renewables curtailment; • Minimise the thermal groups that need to be dispatched; • Maximise the lifetime of the hybrid ESS components. • Maintain frequency Nadir and RoCoF within the defined limits.

Assumptions
The local regulatory framework allows the system operator to install and operate storage devices.
Load and renewable generation forecasting algorithms are implemented and running locally. Outputs from these algorithms can be obtained from local SCADA.
Generation dispatch algorithm is implemented and running locally. Outputs from this algorithm can be obtained from local SCADA.
The multi-temporal optimisation algorithm is implemented and running in a virtual machine at INESC TEC and has access to the island's SCADA (only selected information) through REST APIs.
The multi-temporal optimisation algorithm includes Nadir and RoCoF-related restriction defined through a previously trained ANN.
The ANN used to define Nadir and RoCoF-related restrictions was trained using: • The most relevant contingencies for the island system, which are defined and characterized in a local database that can be accessed remotely. • Trustworthy network/assets data for dynamic simulations provided by the system operator.

Narrative of Use Case
This use case describes how the Madeira Island system operator optimises the operation of a hybrid storage system composed of Li-ion and VRF batteries, pumped hydro and synchronous condensers to: i) Minimise renewables curtailment; ii) Minimise the thermal groups that need to be dispatched; iii) Maximise the lifetime of the hybrid ESS components; iv) Maintain frequency Nadir and RoCoF within the defined limits. To accomplish this objective, a mix of existing and newly developed algorithms (hereafter referred to as "the procedure") will be used, as described in the following steps: 1. The system operator wishes to define the optimal Li-ion battery SOC, VRF battery SoC, synchronous condensers operating point and renewables operating point for a given time interval between '$t_i - t_f$'. For that, he triggers the procedure providing the inputs '$t_i - t_f$'. 2. The first step of the procedure is running the load/renewable generation forecasting algorithms for '$t_i - t_f$'. Load and renewable generation forecasts are saved in the local SCADA.

3. The second step of the procedure is running the dispatch algorithm for '$t_i - t_f$'. Thermal and hydro units dispatch status is saved in the local SCADA.

4. The third step consists of running the multi-temporal optimisation algorithm for '$t_i - t_f$', which performs the following sequential tasks:

   a. Accesses the local SCADA through a REST API to retrieve load/renewable generation forecasts and thermal/hydro units dispatch status for '$t_i - t_f$'.

   b. Runs the optimisation problem with the following characteristics:

      i. Objective function: $Min\ Cost\ (Ren\_Curt, HESS\_Degrad, Sync\_Cond)$

      ii. Subject to security constraints:

         - key frequency indicators within predefined limits ($RoCoF\ and\ Nadir$);
         - $Generation\ units\ capacity\ limits$;
         - $ESS\ limits\ and\ power\ ramps$;
         - $Thermal\ units\ power\ ramps$;
         - $Minimum\ up\ and\ down\ times\ of\ thermal\ units\ and\ synchronous\ condensers$ $;$
         - $Hydro\ reservoirs\ water\ storage\ capabilities.$

      iii. Decision variables:
      $Li - ion\ SoC; VRF\ battery\ SoC; Synchronous\ condensers\ operating\ point$
      $; Renewables\ opeing\ point.$

   c. If the RoCoF and Nadir are far from their limits (specific criteria to be defined), go back to point 3 (second step) and re-run the dispatch algorithm for '$t_i - t_f$' with the removal of one thermal unit. Otherwise, store the decision variables in the local SCADA.

5. In the fourth step, the system operator retrieves from the SCADA the optimised decision variables and implements them during '$t_i - t_f$'.

Actor Name	The roles of the actor	
EEM (as primary actor)	EEM is the primary actor in this use case. As system operator, it is EEM that requests a service from the system under discussion and that aims at achieving the use case main objective.	
Renewable energy companies (as secondary actors)	Companies investing in renewable generation facilities are external actors as they are who provide the renewable curtailment service. They may also be regarded as external actors since they a stakeholder with a clear goal: minimise renewables curtailment.	

Madeira regional government (as an external actor)	The Madeira regional government is considered a stakeholder in this use case, as they have a significant interest in maximising local renewable generation to progressively decarbonise the island.	
Electricity network clients (as external actors)	The customers of Madeira Island's electricity networks are considered stakeholders in this use case, as they have a significant interest in ensuring the resilience of the power grid.	

6.6 ENHANCED VRFB PERFORMANCE: ISOLATED POWER CONVERTERS, CONVERTERS WITH WBG SEMICONDUCTORS, ELECTROLYTE ADDITIVES, MADEIRA ISLAND – PORTUGAL (USE CASE PT 2)

Scope	VRFB's present some operational challenges when it comes to system scale-up and long-term operation. One of the challenges is regarding system scale-up, *i.e.* when VRFB stacks are connected in series to increase the system voltage, there is a loss in efficiency due to the shunt currents occurrence. Another challenge is regarding Vanadium electrolyte precipitation, mostly correlated with high temperature operation (around 40 °C), where solid particles of Vanadium ions are formed compromising the battery operation and lifespan through capacity loss, electrolyte's imbalance, membrane fouling, and/or increased resistance (obstruct the flow of the electrolyte). Additionally, another important aspect when it comes to the battery lifespan, is to ensure that stacks remain sealed for long time, as electrolyte leakage results in fast decay of battery lifetime and contamination of the leaked electrolyte.
Objective(s)	Enhance VRFB performance focused on: • Development and application of isolated DC/DC power converters to mitigate shunt currents occurrence. • Identification/development of electrolyte additives and development of additive dispensers to prevent electrolyte precipitation. • Research and development of self-healing additives to fix electrolyte leaks.

Assumptions
• VRFB BMS provides accurate state estimation of the SoC, temperature, and leaks.
• VRFB communication protocol is provided by the manufacturer (enabling the interoperability with the additional subsystems).

Narrative of Use Case
This use case describes the three planned action lines to enhance the VRFB performance and fulfil with the use case objectives. To accomplish this objective, three different action lines will be applied to fulfil each of the objectives: 1. Shunt-currents occurrence mitigation: development of high-efficiency isolated DC/DC converters (>98%). The use case will allow the connection of the negative pole of each stack to a common ground avoiding scaling the voltage introduced by the direct series connection of the stacks and consequently reducing the voltage across each stack and ground (responsible for increasing the shunt-current phenomena).

2. Electrolyte precipitation dispenser:
    i. Identification of the main conditions that trigger the electrolyte precipitation:
    ii. Manage battery operation to avoid reaching operation at high temperatures.
    iii. Identification/development of additives that prevent operation in the identified conditions highlighted in i.
    iv. Validation of the identified/developed additives at cell level.
    v. Development of an additive dispenser that can actively provide additives when the battery requires it.
    vi. Validation of the developed technique at stack level.
    vii. Implementation and validation of the proposed technique in the demo prototype (depending on the solution resulting costs).

3. Self-healing additives: Research and development of compounds compatible with the electrolyte that solidify in contact with oxygen.
    i. Identification of promising compounds.
    ii. Development of additives.
    iii. Test and validation of the additives at cell level*.

*Validation on the demo prototype would require forcing leaks to prove the concept, compromising the overall demo operation.

Actor Name	The roles of the actor
VRFB manufacturers (as external actor)	VRFB manufacturers are primary actors in this use case. Manufacturers as VRFB providers will benefit directly from the project outcomes allowing to increase their system performance in terms of efficiency and lifespan.
Storage system integrators (as external actor)	Storage system integrators are primary actors in this use case as they will benefit from the hybridization system strategy and respective and project outcomes.
EEM (as primary actor)	EEM is the primary actor in this use case. As system operator, it is EEM that requests a service from the system under discussion and benefit directly from the characteristics of the demo unit.
Renewable energy companies (as secondary actors)	Companies investing in renewable generation facilities are external actors as they are who provide the renewable curtailment service. They may also be regarded as external actors since they are stakeholders with a clear goal: minimise renewables curtailment.
Madeira regional government (as secondary actor)	The Madeira regional government is considered a stakeholder in this use case, as they have a significant interest in maximising local renewable generation to progressively decarbonise the island.
Electricity network clients (as secondary actors)	The customers of Madeira Island's electricity networks are considered stakeholders in this use case, as they have a significant interest in ensuring the resilience of the power grid.

7 CONCLUSIONS

This deliverable performed a detailed literature review on the most popular storage solutions currently available and provided a more in-depth analysis of the storage technologies that are involved in the demonstrations of the i-STENTORE project. The combination of storage technologies in forming HESSs was also studied, as well as the specific HESS's that exist in the project. The specific advantages that these combinations introduce were elaborated on. The different barriers for more widespread ESSs deployment, across several dimensions were presented. To this direction a survey was also conducted with the participation of stakeholders from several countries involved in the i-STENTORE project. The survey and the literature review highlighted societal, technological, economic and regulatory barriers, which were presented in detail. The regulatory state-of-the-art was also explored and presented within this Deliverable. Finally, a first version of the pilots' Business Use Cases (BUCs) was presented. These BUCs will be updated as the project progresses and each time they will be presented in greater detail in the upcoming deliverables of WP2.

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