i-STENTORE

innovative Energy Storage TEchnologies TOwards increased Renewables integration and Efficient Operation

D3.1 I-STENTORE ENERGY STORAGE TECHNOLOGIES EVOLUTION (1ST TECHNOLOGY RELEASE)

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Abstract	This deliverable describes the i-STENTORE demonstrators' configuration, as well as the technological assets available with a focus on the storage components. It also presents the main objectives of each demonstrator, the services that will be implemented and the main innovations to be achieved during the course of the project. This deliverable is the 1st part of 3 consecutive and evolving deliverables that aim at describing the state-of-play of each demonstrator as the project progresses and the evolution on the technology/services deployment.
Keywords	Demonstrators, Technological assets, Services provision, Data exchange

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PEER REVIEWERS

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REVISION HISTORY

Version 1	15/06/2023	Initial structure draft
Version 2	15/09/2023	ToC finalised
Version 3	31/10/2023	Initial contribution from each demonstrator
Version 4	25/01/2024	Final contribution from each demonstrator
Version 5	15/02/2024	Final peer-reviewed version

TABLE OF ABBREVIATIONS AND ACRONYMS

APV	Agri-Photovoltaic
AWS	Amazon Web Services
BESS	Battery Energy Storage System
DC-AC	Direct Current to Alternate Current
DC-DC	Direct Current to Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operator
EEM	Eletricidade da Madeira
EMS	Energy Management System
EV	Electrical Vehicles
FMS	Furnace Monitoring System
HESS	Hybrid Energy Storage System
HOCS	Hierarchical Operation and Control System
HVAC	Heating, Ventilation, and Air Conditioning
HV/MV	High Voltage to Medium Voltage
IS	Individual Section

LIB	Lithium-ion Battery
$LiFePO_4$	lithium iron phosphate battery
LIFO	Last-In-First-Out
MCH	Multi-Charging Hubs
MV/MV	Medium Voltage to Medium Voltage
OCPP	Open Charge Point Protocol
PCS	Power Conversion System
PLCs	Programable Logic Controllers
PMU	Phase Measurement Units
PV	Photovoltaic
REC	Renewable Energy Communities
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SO	System Operator
SoC	State of Charge
SR	Spinning Reserve
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
V2I	Vechicle-to-Infrastructure

V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VESS	Virtual Energy Storage System
VRFB	Vanadium Redox Flow Battery
VSSC	Virtual Synchronous Synchronized Control

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EXECUTIVE SUMMARY

D3.1 is a report covering the first technology release within the i-STENTORE project. This deliverable examines the configuration and the main technology assets across the five distinct demonstrators of the project.

The document structure, together with a brief description of the contents of each chapter, is provided in the following points:

- **Demo 1 - 1 Molten glass thermal storage for an increased uptake of renewable energy:**
    - Demo 1 Overview: summary of the Slovenia electrical grid used in the pilot.
    - Technological Assets: Presents the array of assets integrated in Demo 1, including a hybrid regenerative glass furnace and a rooftop power plant.
    - Demo 1 Objectives: Details the specific objectives set for Demo 1, such as leveraging molten glass for thermal storage and achieving higher carbon neutrality in glass manufacturing.
    - Main Innovations of Demo 1: Highlights the pioneering load-shifting strategy in the glass melting sector, a first-of-its-kind demonstration.
- **Demo 2 - Pump hydro Storage system combined with BESSs:**
    - Demo 2 Overview: Description of the Madeira Island electrical grid.
    - Technological Assets: Details the diverse Hybrid Energy Storage System (HESS) in Demo 2, featuring Li-ion batteries, Vanadium Redox Flow Batteries (VRFB), pumped hydro and synchronous condensers.
    - Demo 2 Objectives: Describe the strategic goals of the pilot, including secure integration of renewable energy sources (RES) and system management through a multi-featured optimization algorithm.
    - Main Innovations of Demo 2: Highlights the utilization of VRFB technology and Li-ion batteries for secure RES integration in Madeira Island.
- **Demo 3 – Virtual Energy Storage System for Renewable Energy Integration:**
    - Demo 3 Overview: Outlines the featured power system and its main technological assets.
    - Technological Assets: Describes the $LiFePO_4$ batteries and the VRFB, integrated into the Hierarchical Operation and Control System (HOCS).
    - Demo 3 Objectives: Outlines the three core objectives of market arbitrage, ancillary services to the Transmission System Operator (TSO), and grid services to the Distribution System Operator (DSO).

    - Main Innovations of Demo 3: Describes the economic dynamics of using stand-alone storage systems in balancing markets and the novel approach of batteries as essential assets in distribution and transmission networks' infrastructure.

- **Demo 4 - Cooperative Modular Multi Hybrid ESS for E-mobility Services:**
    - Demo 4 Overview: Summarises the Italian electrical grid used in the pilot highlighting the Electrical Vehicle (EV) charging network.
    - Technological Assets: Describes storage systems based on hybrid battery technology, battery swap technology for efficient EV charging, PV technology and modular AC/DC Smart Micro-Grid architecture for optimised power flows.
    - Objectives: Establish an AC microgrid to offer innovative mobility and energy flexibility services. Addresses challenges associated with EV charging impacts on AC power grids. Contributes to the sustainability of the energy infrastructure in Campania.
    - Main Innovations of Demo 4: Integration of a hybrid storage system within the ultra-fast charging station to counteract power variations during EV recharge and extend battery lifespan. Optimal management of the microgrid using strategies based on optimal power flow algorithms, ensuring real-time control and efficient offline scheduling operations.

- **Demo 5 - Kielen, Luxembourg:**
    - Demo 5 Overview: Brief description of Luxembourg electrical grid used in the pilot.
    - Technological Assets: A 4.2 MWp wind turbine and a 2.4 MWp PV plant, ensuring an annual yield exceeding 13.7 GWh. Includes a hybridized energy storage system with a Proton Exchange Membrane for "Green hydrogen" production (2.5 MWel) and a utility-scale Li-Ion battery (500 kWh, 1 MW).
    - Demo 5 Objectives: Demonstrates an innovative energy storage combination in an Agri-photovoltaic (APV) plant to optimize energy use. Provides grid support services, reducing energy-related costs and improving grid reliability. Explore hydrogen as a market vector for local industries.
    - Main Innovations of Demo 5: Optimization of energy performance for the APV plant and related processes. Enhancement of grid reliability and power quality by providing flexibility and ancillary services. Demonstrates the role of hydrogen not just in storage flexibility but also as a market commodity, contributing to improved business cases for APV plants.

Considering i-STENTORE scope, D3.1 proves the project's commitment to technology improvements and storage hybridization. As described in the document, each demo plays an important role in finding new ways of storage hybridisation, achieving a more efficient integrated system.

1 INTRODUCTION

The i-STENTORE project is formed by 5 demonstrators. These demonstrators will combine different types of storage technologies creating Hybrid Energy Storage Systems (HESS). HESS take benefit of the advantages each technology has and tries to mitigate the disadvantages of each one by combining different technologies aiming at a more robust and versatile storage system.

Recent concerns in climate change have pushed a paradigm shift in electrical generation aiming at a cleaner and carbon neutral generation. To achieve these goals, the total renewable installed capacity is increasing worldwide. The Renewable Energy Systems (RES) has a sustainable approach relying on natural resources that are not exhaustible during human timeframe. These sources are intermittent and uncontrollable thus RES power output fluctuates and can't be fully controlled. The power output fluctuation from RES creates problems sustaining the electrical grid, reduces system's inertia reflecting more risks to the whole system's stability and security.

ESS mitigates the problems generated by the unpredictability of RES storing energy when demand is lower than supply and vice-versa but also providing ancillary services to the grid increasing overall system's security. There are various ESS technologies and despite ongoing efforts to increase the maturity of these technologies and even develop new ones, there's still technologies with low TRL levels. The current TRL levels indicate that there's room for the industrial and scientific community to further evolve these technologies and especially to try different combinations of technologies into HESS.

D3.1 focuses on the technology assets improvements as well as HESS improvements. In a nutshell, each demo will try to reduce renewables curtailment, increase system stability, get technological advancements in the storage systems, contributing to a more sustainable environment.

2 DEMO 1 MOLTEN GLASS THERMAL STORAGE FOR AN INCREASED UPTAKE OF RENEWABLE ENERGY OVERVIEW

Steklarna Hrastnik (HRAS) is an innovative manufacturer of premium container glass products with more than 160 years of tradition, located in Zasavje, a Slovenian coal region in transition. The target market sector is packaging container glass for spirit glass bottles (Figure 1) and perfume bottles as shown below. HRAS produces approximately 80.800 tons of glass each year.

FIGURE 1: SPIRIT GLASS BOTTLES (CREDITS: STEKLARNA HRASTNIK)

HRAS is faced with the threats of rising energy and carbon (EUA) prices combined by energy insecurity driven by geopolitical instability. Therefore, HRAS recognizes the utilisation of local renewable energy sources (RES), through both increased electrification of the glass production process and the use of clean energy vectors (e.g., hydrogen), as a necessary step for a secure and clean future.

FIGURE 2: STEKLARNA HRASTNIK'S PRODUCTION SITE SPECIAL

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, glass furnaces have up to 5-10 % of their energy demand met using electricity (boosting.) HRAS system aims to manufacture high quality container glass with an electric rate of up to 41 % (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.

2.1 DEMO 1 TECHNOLOGICAL ASSETS

DEMO 1 will be implemented in Steklarna Hrastnik's existing production site in Hrastnik, Zasavje, where the new hybrid regenerative furnace is being constructed. The site has been in operation since 2005 and has an overall area of ca. 16.400 m2. The site infrastructure includes: power supply - 20 kV connection directly to the distribution network with a max power of 7000kVA, gas supply – connection directly to the transmission network (3157 Nm3/h), flue gas treatment (electrostatic precipitator), batch charging system, glass conditioning system with 4 forehearths, 4 Individual Section (IS) machines, 4 annealing furnaces and a plant cooling system.

Apart from the first-of-its-kind hybrid regenerative furnace with 170 tpd capacity, the following equipment will be utilized in the use case of DEMO 1 (Figure 3):

- 170 tpd hybrid end-fired regenerative glass furnace with 4500 kVA of installed electric power (boosting & barrier boosting system);
- 521 kWp PV rooftop power plant;
- Furnace Monitoring System (FMS) for combustion control, refractory corrosion and batch monitoring;
- Flexibility platform developed by project partner ComSensus (COMS)

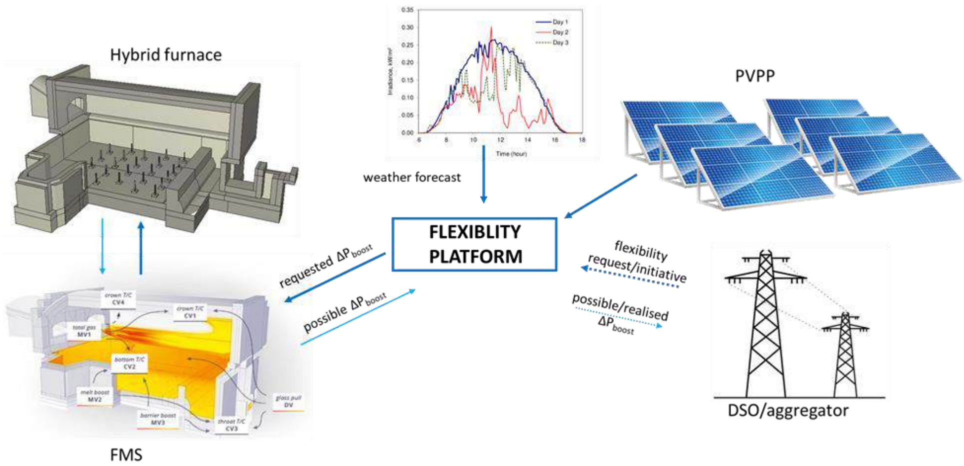

FIGURE 3: DEMO 1 USE CASE

The electric heating or boosting system of the hybrid regenerative furnace is supplied by three barrier (3x300 kVA) and two boosting (2x1800 kVA) 3-phase transformers. The 1800 kVA transformers are connected directly to the new 20 kV MV switchgear, while the 300 kVA transformers are connected to the 0,4 kV connection (LV distributor). The FMS, which is currently being commissioned, integrates with the furnace's sensory equipment (thermocouples, flow meters, energy meters, gas probes, pressure probes, IR camera) and Programable Logic Controllers (PLCs) though an OPC server, which will also be used for the integration with the flexibility platform developed by COMS. The latter will also be integrated with the monitoring app of the PVPP's inverter.

2.2 DEMO 1 OBJECTIVES

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.

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 ancillary services to the power grid.

The innovative hybrid regenerative furnace is a first of a kind demonstration of load shifting in the glass melting sector. This makes drawing parallels with other projects difficult, as the closest equivalents are similar melting furnaces used in other sectors (such as electric arc furnaces). 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 [1]. 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 [1].

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 [1].

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 1.

TABLE 1: COMPARISON OF TECHNICAL FLEXIBILITY POTENTIALS FOR THE ELECTRIC ARC FURNACE, RAW MATERIALS MELTING FURNACE AND CONTAINER GLASS PRODUCTION IN GERMANY [1].

	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 the scheduling of 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 [2].

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 [3].

2.3 MAIN INNOVATIONS OF DEMO 1 OF I-STENTORE

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. In contrast to other load shifting applications in high temperature applications, 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.

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.

3 DEMO 2 PUMP HYDRO STORAGE SYSTEM COMBINED WITH BESSS OVERVIEW

The Madeira Island is contained within the Madeira archipelago, which is constituted by four islands: Madeira, Porto Santo, Desertas and Selvagens. Only the first two are inhabited. Being located 1000 km away from Lisbon, in the North Atlantic Ocean, these two islands are one of the seven European Outermost Regions. The Madeira Island has an area of 741 km^2 with a population of 246,000 of which 106,000 live in Funchal (the region's capital) according to 2021 censos. Tourism plays a key role in local economy receiving over 1 million tourists in the first semester of 2023 alone. Regarding the Madeira Island Power System, *Empresa Eletricidade da Madeira SA* (EEM) is a vertically integrated company hosting generation, transmission, distribution and retailing activities in Madeira and Porto Santo. EEM is responsible for meeting the island's electrical needs and the quality of the electricity supply services. EEM has exclusivity regarding transmission, distribution and electric energy retailing activities. Regarding energy production activity, it remains open to independent producers, which typically explore renewable based projects (solar and wind) under long term feed-in tariffs.

Regarding generation in Madeira Island, the total installed power capacity is 374.6 MW, with a peak demand of 144.55 MW. The power generation mix is strategically designed to meet the energy needs efficiently, comprising [4]:

- **Thermal (Mazut):** 2 plants, 150 MW (52.2%)
- **Thermal (Natural Gas):** 1 unit, 56 MW (14.4%)
- **Hydro:** 77 MW (9.8%)
- **Wind:** 63 MW (15.5%)
- **PV (Photovoltaic):** 23 MW (3.3%)
- **Solid Waste:** 8 MW (4.8%)

Figure 4 presents an overview of the emitted energy to the grid considering the type of technology. The grid has a high penetration of thermal based generation since mazut and natural gas accounts for 66.6% of the total installed capacity and particularly due to the fact that the other sources are not controllable (renewable energy sources). Considering the size of the grid and its isolation, it's difficult to reduce the dependency on thermal groups. Therefore, more storage is needed to increase installed power and electricity generation from renewable sources.

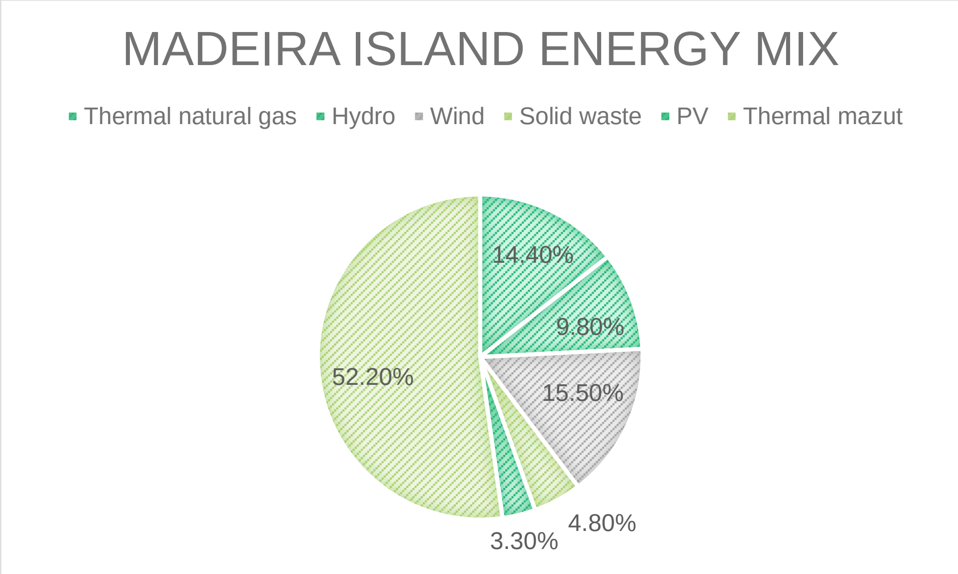

FIGURE 4: MADEIRA ISLAND ENERGY PRODUCED BY TYPE OF TECHNOLOGY [4]

All the sources combined contributed to a total energy emission to the grid of 874 GWh.

Considering the main transmission and distribution infrastructure, the network is essentially comprised of High Voltage to Medium Voltage (HV/MV) and Medium Voltage to Medium Voltage (MV/MV) substations and transmission and distribution lines. The transmission grid operates at 30 kV and 60 kV. As of 2022, a total of 32 substations were operational, with 26 dedicated to supplying the Medium Voltage (MV) network. The remaining three substations are exclusively designed for facilitating energy flow between voltage levels of 60 kV and 30 kV. The predominant operating voltage within the MV network is 6.6 kV, with occasional use of 30 kV in specific scenarios in the Palheiro Ferreiro, Santo da Serra and Machico substations. As of 2022, Madeira Island hosts a total of 1678 secondary substations, of which 1635 operate at 6.6 kV, and 43 are configured for 30 kV.

Currently, Madeira Island has 2 hydro power plants with pumping capacity, Socorridos and Calheta III with 11.25 MW and 16.5 MW of installed power, respectively. These plants use the pumping capacities as a ESS, allowing an increase on wind power. As of 2022, the billed energy and the self-consumed energy from hydro power plants with pumping capacity accounted for 797.2 GWh out of 867.46 GWh of the total emitted electricity to the grid from those sources.

It is planned to install a new Li-ion battery in the Madeira Island with a minimum capacity of 15MW/15MWh, providing more storage capacity to the island that already has a Li-ion storage system with 16MWh.

Madeira Island plans to expand its renewable energy infrastructure including a reconfiguration of the hydro power plant in Serra de Água with installed power of 10.8 MW and higher capacity to store water, allowing to integrate more renewable energy. Madeira Island plans to install a synchronous condenser with minimum power of 15 MVA to regulate voltage, provide short-circuit power and increase inertia of the system. EEM will also remodel the groups and adductor channels in Calheta I, which will increase the amount of energy produced but also impact Calheta II that is connected to Calheta I and this will increase the water capture [4].

3.1 DEMO 2 TECHNOLOGICAL ASSETS

Demo 2 on Madeira Island features a Hybrid Energy Storage System (HESS), involving a mix of proprietary components and technologies. The system incorporates a Li-ion battery, hydro power with reservoirs and it will incorporate a Vanadium Redox Flow Battery (VRFB) and synchronous condensers. An optimisation algorithm will be developed to manage the whole power system.

The technologies integrated in the HESS are the following:

- Vanadium Redox Flow Battery (VRFB) is a technology used for energy storage. This technology has a long lifecycle, high efficiency, and can store energy for extended periods. VRFB stores energy into two tanks containing vanadium electrolytes, separated by a membrane. During charging and discharging, the electrolytes flow through an energy converter (electrochemical cell or stakes), generating electricity. The advantage of VRFB is its scalability, as the energy storage capacity can be easily increased by adding more electrolyte solution and increasing the stakes that are connected.
- Li-Ion battery is a widely used technology in energy storage, with high energy density, long lifecycle, 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.
- 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 long lifecycle that can be used to reduce renewable energy curtailment.
- Synchronous condensers are DC-excited synchronous machines characterised by a large rotating generator whose shaft is unconnected to any driving equipment. Its primary function is voltage regulation and stability by continually generating or absorbing adjustable reactive power. Furthermore, it contributes to increased short-circuit strength and frequency stability through the provision of synchronous inertia.

The Li-ion Battery Energy Storage System (BESS), which has 24 MVA and 16 MWh of capacity, can operate in two modes: grid forming or grid following. In grid forming the system enhances the island's ability to quickly respond to frequency variations, enabling therefore the integration of more renewables in the island.

The VRFB is being developed by VGLAB that will install and test the battery with different electrolyte additives with the target of enhancing the battery's lifetime. The VRFB is shown in Figure 5 and has the following characteristics:

- Power capacity: 50 kW;
- Energy capacity: 50kWh;
- Comprising 12 stacks, each with a power output of 4 kW;
- Incorporates a 10% overcharge capacity in each stack, enhancing flexibility during peak demand periods;
- Variable output voltage ranging from 40 to 63 V across the stacks;
- Housed within a compact 20 ft container with thermal insulation and Heating Ventilation and Air conditioning (HVAC);
- Features a substantial 2,127-liter electrolyte tank;
- Utilizes centrifugal pumps to circulate the vanadium-based electrolyte efficiently;
- Equipped with DC-DC converters to regulate voltage within individual stacks;
- Incorporates DC-AC converters (400V 3 phase).

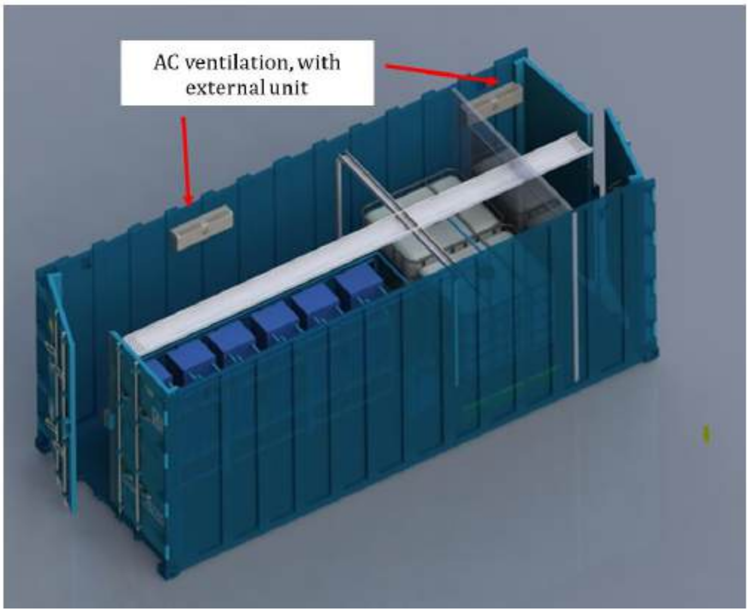

FIGURE 5: VRFB HOUSING

The island also features two hydro units with pumping capabilities, one with 24.3 MW installed power and 3 x 3.75 MW pumping installed power. The second unit, equipped with pumping capacity, has a nominal power of 23.7 MVA / 15 MW and a capacity of 16.4 MW. These hydro units play a dual role, not only generating power but also offering the flexibility of energy storage and pumping capabilities both in times that production surpasses demand and vice-versa.

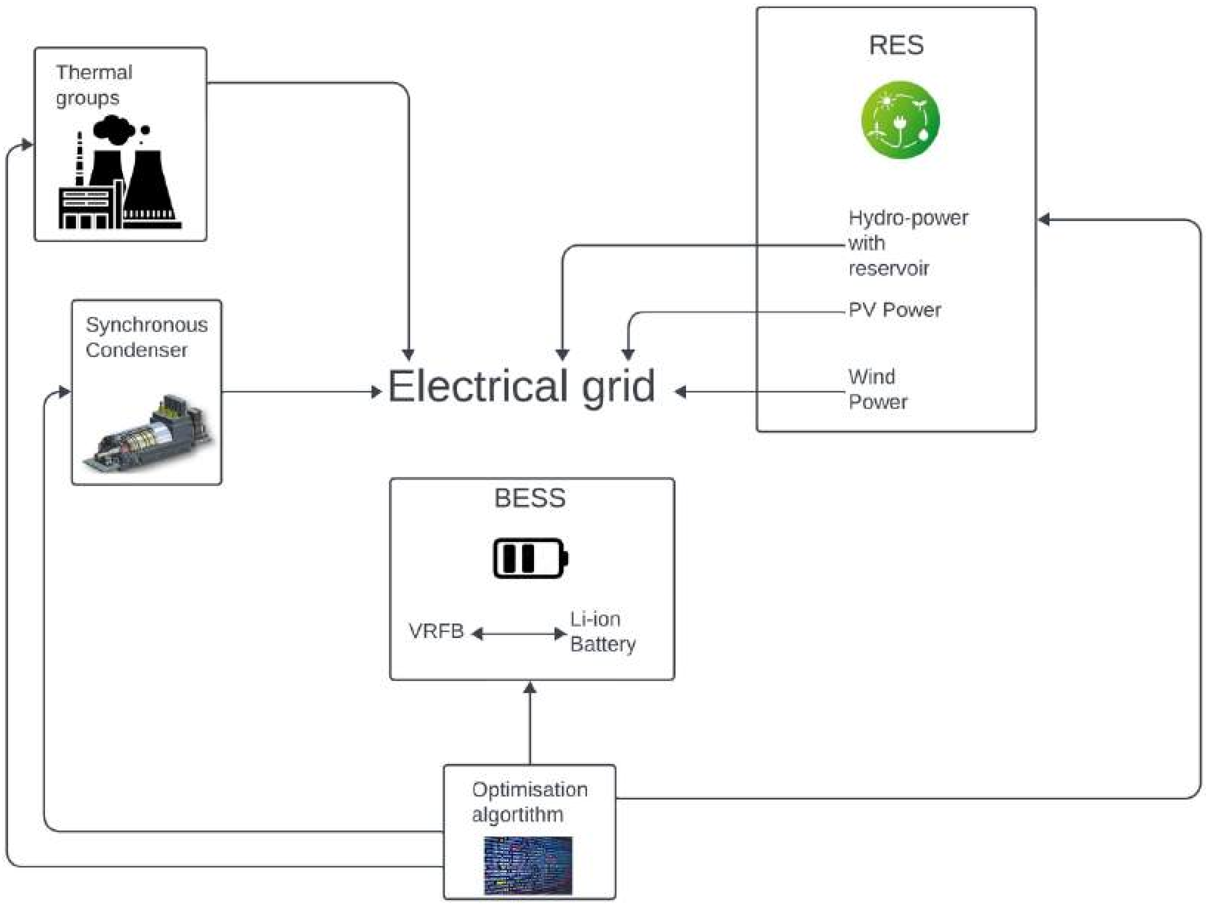

FIGURE 6: MADEIRA ISLAND POWER SYSTEM OVERVIEW

The HESS integrated in demo 2 will be managed in i-STENTORE to smooth photovoltaic ramps, regulate grid frequency, and reduce renewable energy curtailment.

The referred multi-temporal optimization algorithm is currently under development by INESC in collaboration with EEM. This algorithm uses an economic dispatch approach with dynamic security constraints aiming at increasing the renewable energy integration in the island. The algorithm and its integration with the Madeira Island power system is shown in Figure 6.

The data flows required to enable an effective implementation of the optimisation algorithm are depicted in Figure 7. The System Operator (SO) initiates the process by requesting a new dispatch from its local server, which, in turn, communicates with the Supervisory Control and Data Acquisition (SCADA) system to obtain updated data. Subsequently, the local server provides the INESC TEC virtual machine with the latest data and a request to execute the optimization algorithm. The INESC virtual machine then delivers the results to the SO, EEM. The INESC virtual machine access various types of data required to run the optimisation process, including:

- Load, reservoirs inflows, solar, and wind generation forecasts, in csv format.

- Thermal and hydro units' dispatch data, available in txt and csv formats.
- Vanadium Redox Flow Battery (VRFB) bands for photovoltaic (PV) ramps and Lithium-ion (Li-ion) bands for spinning reserves (SR).

Following the optimization process, INESC shares essential data with the System Operator (SO), including:

- Charge/discharge setpoints for Li-ion and VRFB batteries.
- Synchronous condensers status and renewables operating points.
- Number of thermal groups necessary.

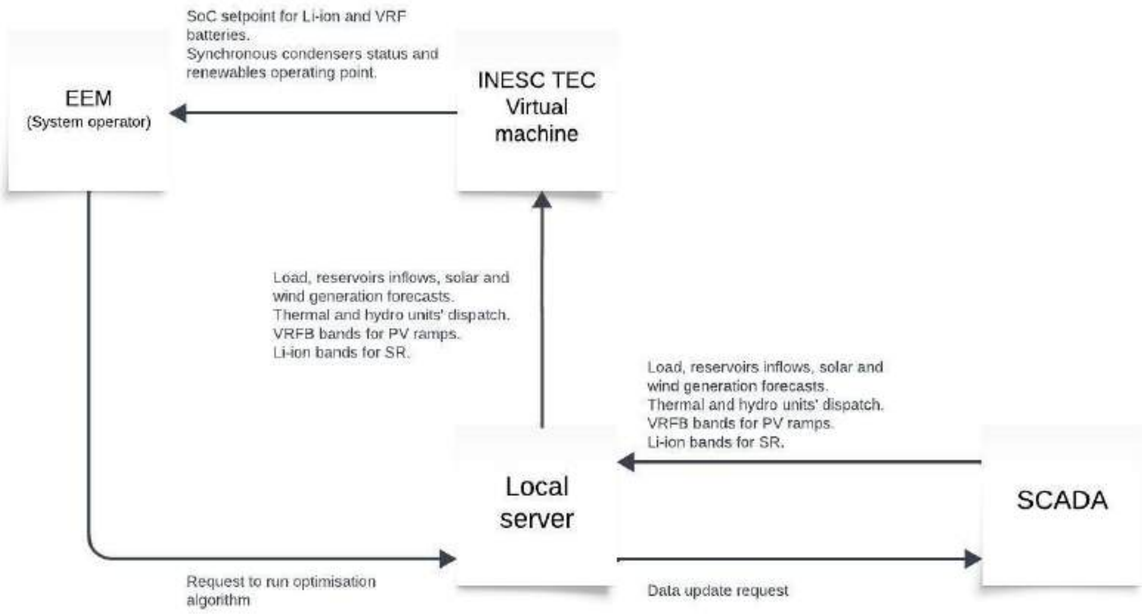

FIGURE 7: MADEIRA DATA FLOW OVERVIEW

3.2 DEMO 2 OBJECTIVES

Demo 2 is strategically designed to address two primary objectives. Contribute to the secure integration of RES in Madeira Island through a judicious management of a fleet of energy storage sources capable of providing responses within multiples time frames and operational purposes.

While no projects had previously used a HESS with the same technologies as the ones used in demo 2, there are relevant initiatives that provide technological advancements and tests in this field of research.

In the context of innovative energy storage systems, HyFlow project uses a super capacitor and a VRFB to meet increasing demand for renewable energy.

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The project seeks to enhance components, hybridization, and improve control algorithms to unlock diverse applications within the grid.
The HyFlow project has a demonstrator-scale of 5kW demonstrator and industry-scale demonstrator of 300kW, with the latter allowing for testing the fastest grid services like virtual inertia. HyFlow is the most relevant project using a VRFB that until today lacks use in large scale.
Much like Demo 2, the HyFlow project tackles specific objectives, aiming to develop high-power vanadium redox flow batteries and supercapacitors. This project uses a multi-temporal optimization algorithm to optimize the power flow between the HESS technologies. Similarly, Demo 2 will have a multi-temporal optimisation algorithm to optimize the power flow between the HESS technologies. However, Demo 2 has more technologies integrated in the HESS and will also provide system services to the grid. Another difference is the deployment location, which, in the case of i-STENTORE demo 2, will be a small island with an isolated grid.
The XFLEX HYDRO project is another project funded by EU that tries to increase efficiency, availability, and flexibility making the hydro plant able to provide ancillary services to the grid in particular FCR (Frequency Containment Reserve), the i-STENTORE demo 2 will also provide FCR along with other services.
In a world transitioning to high Renewable Energy Sources (RES) scenarios, XFLEX HYDRO addresses hydropower generation in ensuring the stability and flexibility of the Electric Power System (EPS).
One of XFLEX HYDRO's demonstrators is the Vogelgrun hydropower plant in France. Here, 4 Kaplan turbine units of 35MW, in service since 1959, will be hybridized with a 300kWh li-ion battery and a 650kW inverter. This aligns closely with Demo 2's approach, that integrates Li-ion batteries and hydro power systems, for grid stabilization and optimization.
This demonstrator tries to increase the longevity of the turbine. Demo 2 of the i-STENTORE also tries to increase the longevity of its components but, instead of reducing turbine tear, it aims at reducing Li-io battery degradation. i-STENTORE demo 2 will also aggregate more technologies in the HESS that will enable the provision of an extended set of ancillary services to the grid.
The InterSTORE project aims to address the lack of energy storage using diverse solutions and technologies with varying characteristics. Its primary objective is to develop an innovative middleware, which virtualizes storage technology, simplifying its integration and use from both an integration platform and monetization perspective. This middleware ensure independence from specific hardware solutions, increase overall efficiency and integration.
InterSTORE's middleware is designed to facilitate the integration of various storage technologies, thus offering a more robust and flexible solution. The project aims to release the middleware as a full open-source product, incorporating existing standards and protocols.
Furthermore, the middleware will be integrated into both open-source and commercial platforms, which will be used in real-life demonstrations to assess user acceptance and economic value. The project considers further plans to ensure the sustained adoption of the solution beyond the project's conclusion. The consortium is committed to continued software maintenance, with the support of the Linux Foundation Energy, and actions to contribute to ongoing standardization activities.

In comparison to the i-STENTORE project demo 2, which focuses on Hybrid Energy Storage Systems (HESS) for grid optimization and stability in a non-market-based island grid context, InterSTORE takes a different perspective. InterSTORE's middleware is aimed at simplifying the integration of various storage technologies, offering more flexibility and options for customers.

InterSTORE emphasis on data monetization and impact analysis. The project seeks to contribute to the development of data hubs that will use that data to maximize economic impact through data utilization. InterSTORE's objectives align with creating a more interoperable and flexible energy storage model, emphasizing data privacy, security, and real-time data sharing.

InterSTORE has 4 living labs in order to achieve the project goals, test the solutions and demonstrate its results. The 1st living lab, Industrial Flexibility Pilot in Portugal has an electrical network that involves PV production systems, electric vehicle (EV) charging points, and an electric energy storage system (ESS) with 320 kW/798 kWh capacity. This lab aims to integrate distributed resources in an industrial context, managing distributed storage, controlling and operating systems to optimize flexibility, and increase capacity at electrical grid nodes with the added BESS.

The 2nd living lab, Commercial Flexibility Pilot in Germany uses the existing infrastructure of the research center in Forschungszentrum Jülich. The infrastructure is composed by electricity grids, heating grids, cooling grids, and a gas grid. It focus on creating software protocols to integrate different distributed storage applications, ensuring interoperability (Interoperable DES).

The 3rd living lab, E-Mobility Flexibility Pilot in Italy operates in both off-grid and on-grid testing modes, supporting testing of AC and DC devices. It features 4 interconnected microgrids (MGs) of varying scales, from 48 VDC to 750 VDC. This demo will demonstrate the system interoperability using common protocols, security, real-time data sharing and utilisation and the development of energy community business models. This lab will allow tests in power converters, ESS, EV charging stations and regenerative grid simulations.

The 4th living lab, Residential Flexibility Pilot in Austria has more than 2500 decentralized units to manage system interoperability in different operational nodes. The lab will have at least two different energy communities to compare different operational modes.

Both projects address critical aspects of the evolving energy landscape, but they do so from distinct approaches. i-STENTORE is more focused on specific applications for grid stabilization, whereas InterSTORE provides a middleware solution with advantages for storage technology integration.

3.3 MAIN INNOVATIONS OF DEMO 2 OF I-STENTORE

In the context of energy storage projects, Demo 2 of i-STENTORE has an innovative Hybrid Energy Storage System (HESS). It is worth noting that while there are several projects in the storage field, only a few have aggregated the amount of technologies present in this HESS. The mix of Li-ion batteries, pump hydro power, synchronous condensers, and Vanadium Redox Flow Batteries (VRFB) is a distinctive feature of this pilot. These assets will be managed by an optimisation algorithm that will provide dispatch commands in order to achieve the

most economic operational point while maintaining dynamic security of the system. The algorithm will give commands to the dispatch centre while maintaining the grid's security trying to achieve the most cost-effective operational point. This combination creates a HESS with a diverse set of capabilities, providing a solution for effectively enhancing grid performance, particularly in the case of a small, isolated grid, such as the case of Madeira Island. Demo 2 will showcase several grid support services that are essential for maintaining grid stability and reliability, especially in contexts with large renewables integration.
One of the challenges involving VFRB scaling-up is the operational temperature (10–40ºC) and concentration of vanadium in the electrolyte. Above 40ºC, vanadium ions in the oxidation state 5+ (VO2+) start precipitating, provoking solid particles' appearance and decreasing the vanadium concentration. Bellow 10ºC, other vanadium species start precipitating as well. Furthermore, these additives also intend to increase the vanadium concentration, in this way increasing the energy storage capacity per litre of electrolyte. Another application involving a specific class of additives is to control electrolyte leakage. These compounds will be applied to develop self-healing strategies to control electrolyte leakage. It is intended to develop/use a compound that, when in contact with, for example, oxygen, blocks where the leakage is happening.

Although the VRFB is a flexible and promising energy storage technology, the scaling-up involves some challenges, as mentioned previously:

- Loss of efficiency when stacks are connected in series – this is done to increase the system voltage, there is a loss in efficiency due to the shunt currents occurrence.
- Stakes efficiency – Operational State of Charge range (SoC), VRFB normally operates between 20% to 80% of SoC to avoid side reactions inside the energy converter.
- Electrolyte leakage - Regarding the electrolyte, the product chain is limited, and the price is subject of the market variations, thus impacting in the price of the technology.
- Lack of development in the additives - The rate of the development and application of additives involves a large amount of experimentation and analysis of empirical data. Hence, it depends on chemical delivery, price, and stock availability.
- Limited studies and suppliers – There's very little large-scale applications with VRFB which will represent a lot of tests. The market still lacks manufacturers of VRFB which represents higher prices and leads to less availability to make more tests since they're expensive.
- VRFB storage – Due to the implications of the battery to integrate the whole VRFB system it is necessary to acquire a custom made shipping container due to the complexity of the container prices and delivery times are high. The assembly of the system within the container must be carefully addressed to make the system as immune as possible to vibration damage during transportation.

Furthermore, there's still lack of projects, advancements, and usage of VRFB. Demo 2 will address this problem contributing to further advancements in the VRFB technology.

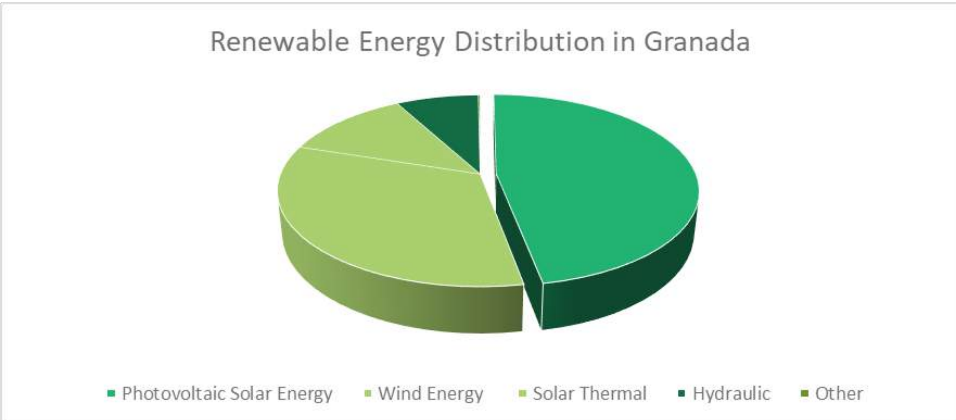
Additionally, the majority of storage projects operate within market-based grids, subject to market dynamics. Demo 2, in contrast, operates in the distinct context of an island grid, where market mechanisms are not present.

4 DEMO 3 VIRTUAL ENERGY STORAGE SYSTEM FOR RENEWABLE ENERGY INTEGRATION OVERVIEW

The province of Granada is located in the southeast of Spain, within the Autonomous Community of Andalusia. The province has a population of 919.700 and, according to the Andalusian Energy Agency, in 2019 there were 5.121.568 supply points and 12 distribution System Operators. Cuerva, the DSO representative in the Spanish demo, is one of them. Cuerva's network counts more than 900 km of distribution lines, more than 500 secondary substations and two substations, one of which is connected to the Transmission System Operator (Red Eléctrica de España). Its network has more than 18.000 supply points and supplies more than 50.000 users with more than 247.000 kWh of electricity per day.

According to the Andalusian Energy Agency, Granada stands out for its large production of renewable energy. According to records at the end of June 2023, the renewable capacity is 1.238,9 MW. Photovoltaics account for 47,1% of generation, while wind power accounts for 32,9%, with the installed capacity summarised in Table 2 below:

TABLE 2: RENEWABLE ENERGY GENERATION MIX OF GRANDA



Technology	Power (MW)	%
Photovoltaic Solar Energy	583,5	47,1
Wind Energy	407,2	32,9
Solar Thermal	149,7	12,1
Hydraulic	96,3	7,8
Other	2,2	0,1

The continuously increasing injection of renewable energy into the system is one of the main challenges for operators, as they must integrate new capacity into their systems while maintaining the correct levels of voltage and frequency. Furthermore, the weather-dependent nature of renewable energy makes the controllability of different generation units complex, along with the operation and planning of the distribution grid.

Storage systems have emerged as an integral solution for this matter due to the control capabilities they offer.

Co-funded by the European Union

In this context, the province of Granada provides an ideal setting for Demo 3, which will integrate two energy storage technologies: a Lithium-ion battery (LIB) and a Vanadium Redox Flow battery (VRFB) into the distribution grid operated by Cuerva. These assets will be controlled by a Hierarchical Operation and Control System (HOCS) and integrated into a digital platform providing Virtual Energy Storage System (VESS) capabilities.

The operation of the assets will be governed by optimization algorithms developed to deliver various services, as detailed in the following sections. These algorithms will take into account the production of different renewable energy plants situated on the same distribution grid.

These two storage technologies possess distinct characteristics that can complement each other. Vanadium Redox Flow batteries offer an extended cycle life and overall lifetime, remaining largely unaffected by high depth of discharge. Their notable advantage includes low degradation. However, their round-trip efficiency is comparatively lower than that of Lithium-ion batteries.

On the contrary, Lithium-ion batteries exhibit features such as fast charging, high round-trip efficiency, and rapid response times, rendering them suitable and flexible for power and energy applications. Nevertheless, in contrast to VRFBs, high depth of discharge in LIBs results in degradation and diminishes their overall lifespan.

4.1 DEMO 3 TECHNOLOGICAL ASSETS AND CONFIGURATION

In this section, the energy storage assets of Demo 3 will be described, presenting their integration and configuration within the Hierarchical Operation and Control System (HOCS) and the demo platform.

With respect to the LIB, the battery enclosure is a small custom-made compartment that houses three racks of Narada LiFePO4 2C batteries. This system is designed to provide 0.5 MWh of storage capacity and 1 MW of power. The enclosure also contains all the necessary ancillary systems to ensure the safe operation of the batteries. In addition, the system includes a Danfoss liquid-cooled 1000 kW power converter housed in a separate enclosure from the batteries.

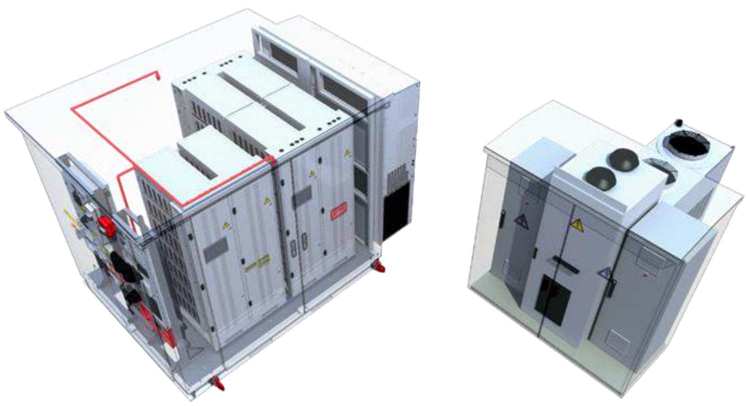


FIGURE 8: LIB BATTERY OF DEMO 3

The VRFB energy storage system consists of a 250 kW power module and a stored energy capacity of 625 kWh. Housed in a 40ft container, it encompasses the battery's power components such as stacks, pumps, the complete hydraulic system, the PCS (Power Conversion System), and a lifting transformer. The electrolyte is stored in two external tanks. This battery system delivers a steady power output of 250 kW for a duration of 2.5 hours, catering to diverse applications.

The Hierarchical Operation and Control System (HOCS) plays a crucial role in facilitating the dynamic interactions between the renewable power plants, the Vanadium Redox Flow battery and the Lithium-ion battery within Demo 3. The HOCS is at the forefront of enabling real-time coordination and ensuring participation in current and future market infrastructures. Through this synchronization of different energy resources, the HOCS optimizes functionality, allowing these components to collectively provide grid support services while effectively managing battery degradation.

At the heart of Demo 3's energy management strategy lies the HOCS, which is characterized by a hierarchical structure comprising three well-defined control layers. The lower layers are highly dedicated to local control and operation, providing tailored management for each energy asset. This localized approach ensures efficient operation and optimal performance for each individual component.

The middle layer of the HOCS plays a pivotal role in coordinating data exchange with the i-STENTORE Reference Architecture. This integration not only facilitates communication but also aligns with the overarching principles of the project, enhancing interoperability and fostering data trust. The upper layer is strategically designed for market operations, overseeing the trading of energy and services within the Virtual Energy Storage System.

The adaptability of the HOCS goes beyond its internal hierarchical structure, encompassing integration with external systems crucial for energy management. Specifically, the HOCS is equipped with the ability to communicate with the i-STENTORE middleware, ensuring access to weather forecasting services. Additionally, direct communication with the Supervisory Control and Data Acquisition (SCADA) system of the Distribution System Operator (DSO) enhances the HOCS's capability to gather real-time data and respond dynamically to grid conditions.

Figure 9 presents the conceptual platform architecture of Demo 3, designed to optimize energy management and participation in wholesale markets. The platform consists of four distinct databases tailored for specific temporal data characteristics, forming the backbone of data storage and analysis. The 'static db' serves as a repository for critical information, storing component definitions and user account details essential for access control within the system. In contrast, the 'real-time db' dynamically captures streaming data from component metering devices, including variables such as voltage, current, and power. Operational state information, alarms, and warnings are also housed in the real-time database. This data follows a Last-In-First-Out (LIFO) approach in buffer tables before transitioning to the 'past db.' The 'past db' acts as a valuable resource for the forecast engine, utilizing historical data to generate crucial forecasts, such as energy production and market prices. These forecasts, combined with operational parameters, guide the optimization engine in forming Battery Energy Storage System (BESS) schedules and bids. The 'day-ahead' service stores schedules in the 'future db' before transitioning them to the 'real-time db,' facilitating seamless relay to Virtual Energy Storage System (VESS) units and the market. Forecasts and optimization results are archived in the 'past db' for thorough analysis.

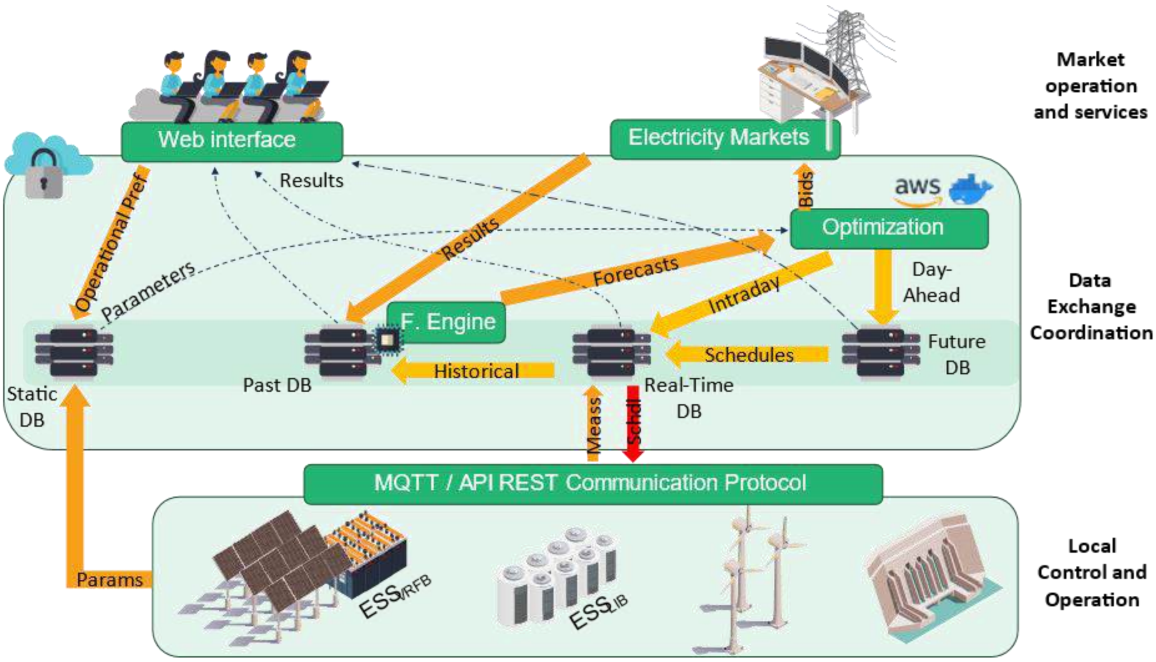


FIGURE 9: HOCS CONTROL LAYERS AND INTERACTIONS WITHIN THE CONTROL SYSTEM.

To efficiently manage these databases, Demo 3 strategically combines SQL, NoSQL, and timeseries database technologies. The interaction between components relies on HTTP requests, and communication between the platform and VESS assets is facilitated through the MQTT and MODBUS protocols, ensuring a robust and responsive system.

The core of Demo 3's operation revolves around mathematical optimization processes integrated into a cloud-based structure hosted on Amazon Web Services (AWS). Figure 9 illustrates the strategic placement of the optimization container within AWS, enabling seamless interactions among diverse cloud components and databases. This platform serves as the central hub for VESS management, providing real-time analysis and continuous data collection from VESS components.

Moreover, the platform excels in optimizing energy trading by evaluating and forecasting data related to energy demand, renewable generation, and market prices. This meticulous process identifies trading opportunities, ultimately enhancing economic efficiency. Operational efficiency is further ensured through the utilization of Docker containers within AWS.

To facilitate user interaction, a web interface is provided, offering real-time data, schedules, and graphical representations. This user-friendly interface empowers stakeholders with the information necessary for informed decision-making, contributing significantly to the overall efficiency and responsiveness of Demo 3's energy system.

4.2 DEMO 3 OBJECTIVES

Demo 3 aims to achieve three main objectives based on the Business Use Cases to be demonstrated within the i-STENTORE project:

1. Market arbitrage and cost minimization

The scope of the Spanish Demo is to increase income through the use of storage solutions in the wholesale market. Therefore, the different technologies involved in the Demo will be managed according to their technical characteristics, the expected production of the different renewable assets and the market status, in order to optimize the SoC of the batteries and their production.

In this specific scenario, the operational strategies of the assets will be developed by considering the production of the following renewable power plants:

- 1 Wind plant with a nominal power of 1.5 MW
- 1 PV plant with a nominal power of 1.8 MW (expected on February 25)
- 1 Hydropower Plant with a nominal power of 2.4 MW

To achieve this objective, the participation of VESS in the wholesale market will be scheduled based on the results of an optimization algorithm.

2. Ancillary Services to the TSO

Another Demo objective is to address the benefits of participating in the tertiary market. To achieve this, a stand-alone battery will be used to offer services to the Transmission System Operator (TSO) through a real balancing market, such as the manual Frequency Restoration Reserve.

This use case is designed to explore the potential profitability of balancing markets for energy producers by focusing on stand-alone connected storage systems. Currently, stand-alone batteries constitute a relatively small portion of most grid-connected storage systems, primarily due to significant uncertainties regarding the return on investment. This objective aims to dispel these doubts and gather empirical data that will provide tangible insights into the viability of stand-alone connected storage systems within the context of balancing markets.

The project entails a comprehensive examination of the economic dynamics involved in using stand-alone storage systems to participate in balancing markets. This includes a thorough analysis of market conditions, regulatory frameworks and operational strategies that can optimize financial returns for energy producers. By actively engaging with balancing markets, the use case aims to showcase the potential revenue streams and economic advantages that standalone connected storage systems can offer.

The project methodology involves the implementation of stand-alone storage systems in a controlled environment and carefully monitoring and recording their performance within the balancing markets (Tertiary Market, mFRR). This empirical data will then be used to assess the economic feasibility, risk factors and overall return on investment associated with integrating stand-alone batteries into the broader energy landscape.

Ultimately, this project aims to fill the existing knowledge gap by providing tangible evidence and insights into the economic viability of stand-alone, interconnected storage systems in balancing markets. Through a combination of empirical data, market analysis and strategic considerations, the use case seeks to provide a comprehensive understanding of the financial opportunities and challenges associated with this innovative approach to energy storage and market participation.

3. Grid Services to the DSO as a Flexibility Service Provider

This objective seeks to demonstrate how a VESS system can effectively support Distribution System Operators (DSOs) by providing Flexibility Services.

By leveraging the regulatory capabilities of batteries, grid operators gain a powerful tool to dynamically control voltage and frequency levels, ensuring the safe and reliable distribution and supply of energy within the electrical grid. Beyond the intrinsic benefits of grid resilience and safety, this approach introduces a novel paradigm where batteries are not merely considered as energy storage but are actively utilized as essential assets within the distribution infrastructure. Through these markets, the following services can be offered:

- Voltage and Frequency Regulation: Stand-alone batteries can significantly contribute to the regulation of voltage and frequency levels within the grid. Their rapid response capabilities enable the fine-tuning of these parameters, maintaining them within safe and optimal ranges. This is especially crucial in the face of variable renewable energy sources that may introduce fluctuations.
- Grid Balancing Services: Flexibility markets offer grid operators the ability to balance the supply and demand of electricity in real-time. Batteries, acting as flexible assets, can charge during periods of low demand and discharge when demand peaks, thereby assisting in the overall stability of the grid.
- Fast Response to Grid Events: Batteries can provide near-instantaneous responses to grid events, such as sudden changes in demand or unexpected outages. This agility enhances the grid's ability to adapt quickly to dynamic conditions, preventing disruptions and maintaining a reliable power supply.
- Integration of Renewable Energy: The variability inherent in renewable energy sources, such as wind and solar, can be effectively mitigated by using batteries for energy regulation. This ensures a smoother integration of renewable energy into the grid, addressing the intermittency challenges associated with these sources.

In summary, this use case not only demonstrates the technical capabilities of stand-alone batteries in regulating grid parameters, but also highlights the wider economic and operational benefits for both grid operators and energy asset owners.

4.3 MAIN INNOVATIONS OF DEMO 3 OF I-STENTORE

The main innovations of Demo 3 in the i-STENTORE project align in different directions. Firstly, there are innovations directly related to the solution adopted for energy storage systems. On the other hand, it is worth mentioning the features related to the integration of different assets into the HOCS and the platforms of the demo and the i-STENTORE project, as well as the way in which optimization algorithms are applied to control the operation of the assets.

In relation to the adopted solution for the LIB, the manufacturer has incorporated several innovative features into this system. Firstly, the battery enclosure is designed to be compact and versatile, incorporating all necessary ancillary systems, protections, and electrical connections. This design minimizes foundation requirements and installation time on site.

Secondly, the power converter utilizes liquid cooling equipment, with the goal of enhancing efficiency and power density, while simultaneously reducing its physical footprint.

In reference to the integration of the Demo assets into the HOCS and the digital platform, the deployment and testing for Demo 3 involve a systematic implementation process, ensuring the successful integration of key features for optimal functionality.

The initial steps include implementing data models in development database servers, followed by the development and deployment of an initial set of APIs. These APIs provide fundamental functionalities, primarily focused on CRUD operations, facilitating seamless interaction with the databases. The testing phase involves validating internal communications and ensuring the integrity of HTTP messages. Furthermore, integration with the optimizer is paramount, enabling data read and write operations from the databases through the APIs.

In a pioneering move, an innovative Hierarchical Operation and Control System (HOCS) will be deployed to govern the dynamics of the Virtual Energy Storage System (VESS). The digital hierarchical control acts as a synchronization system for the active assets of the pilot, utilizing standard communication protocols similar to those employed in communicating with Phase Measurement Units (PMU) in the grid.

Expanding on the reference architecture, a new control layer will be introduced to coordinate the real-time operation of multiple stations interconnected within a specific area of the power grid. A cluster-level controller will regulate the collaborative response of distributed resources in real-time, enhancing stability and robustness. Additionally, the Smart Grid Architecture Model (SGAM) interoperability layers will be revised to organize functionalities and relationships effectively, establishing edge-, fog-, and cloud-computation tiers. This adaptation aligns with the taxonomy and ontology of active energy and storage assets and actors participating in energy systems.

The digital platform, tailored to the specificities of the demonstrator, will offer multiple levels of interoperability and intelligence to Demo 3's VESS. It introduces new functionalities and services designed to facilitate energy management and assist operators in decision-making processes. Covering the high layers of the SGAM, the platform provides user-friendly interfaces and intelligent management tools for planning, operating, analyzing, accounting, and administering energy generation and storage.

These intelligent tools optimize the VESS, minimizing energy costs and generating new income streams by effectively managing interactions with external markets. The platform securely manages the data space and implements necessary mechanisms to interoperate with other platforms and dataspaces, including the i-STENTORE common data governance middleware layers. This comprehensive digital platform ensures efficient energy management and decision-making for Demo 3, focusing on the innovative VESS.

Finally, it is important to mention certain aspects of the optimization strategy. The primary focus of the project is the participation of the Virtual Energy Storage System (VESS) in wholesale markets. Leveraging diverse predictions related to renewable asset production, the optimization algorithm determines the optimal market offer, accounting for the influence of other markets and services. In the subsequent stage, the VESS engages in tertiary balancing services for the Spanish Transmission System Operator (TSO). This involves adhering to

Operation Procedure 1.5, section 3.3, where the tertiary reserve is defined as the maximum power variation in upward or downward directions that can be scheduled within a timeframe not exceeding 15 minutes and must be maintained for at least 30 minutes. The objective is to reconstitute the secondary reserve. Given the Li-ion battery's specifications of 1 MW and 479 kWh, it meets the test outlined in Operation Procedure 3.8, making the VESS eligible to participate.

Furthermore, the VESS's diverse capabilities will undergo testing to showcase its potential in providing flexible services to the Distribution System Operator (DSO). This testing includes the mitigation of congestions or over-voltages. A more in-depth analysis will be conducted to fully explore the application's potential. For Business Use Case 1, an initial optimization model has been developed. This model serves as a testing ground for evaluating the capabilities of the digital platform architecture and deployment.

The main innovation lies in the unique combination of services offered, introducing novel revenue schemes for the VESS to maximize profits and incentivize deployment throughout the Spanish national electricity market. Due to its distinctive capabilities, the VESS has the potential to offer multiple services to the DSO.

5 DEMO 4 COOPERATIVE MODULAR MULTI HYBRID ESS FOR E-MOBILITY SERVICES OVERVIEW

The Italian Demo project envisions a transformed tourism industry in the region, powered by electric vehicles (EV) and battery-based charging points. This ambitious endeavour encompasses a comprehensive approach to promote EV adoption, expand charging infrastructure, and integrate renewable energy sources, all while fostering sustainable tourism practices. At the core of this initiative lies the establishment of Multi-Charging Hubs (MCH) strategically located in key tourist areas. These MCH will serve as hubs for EV sharing, providing convenient access to EV for rental during visitors' excursions. Complementing the MCH are "destination chargers" installed at popular tourist destinations, ensuring easy access to charging for EV drivers exploring these attractions.

To address gaps in fixed charging infrastructure, the project will deploy mobile chargers, offering on-demand charging services. This ensures that EV drivers can always find a charging option, even in remote locations.

Harnessing the power of energy storage systems (ESS) and renewable energy sources, such as solar panels, will ensure a consistent supply of electricity for the charging infrastructure. ESS will store excess energy from solar panels, effectively managing supply and demand, even during periods of low solar production. Preparing the MCH for integration with Renewable Energy Communities (REC) will further enhance their sustainability. This will allow the hubs to tap into local renewable energy sources, reducing their reliance on the main power grid. To streamline the EV charging experience for users, the smartphone app will be developed. This app will enable users to book EV, reserve charging spots, and access real-time charging information.

5.1 DEMO 4 TECHNOLOGICAL ASSETS AND CONFIGURATION

The i-STENTORE Demonstrator 4 is situated in southern Italy, specifically in the Campania region. Its primary objective is to promote sustainable mobility through the widespread adoption of electric vehicles (EV). A crucial aspect of achieving this goal is the establishment of EV charging stations across the region. However, the pulsed nature of the EV charging process, particularly with ultra-fast charging stations, poses challenges, as these stations can become critical loads for AC distribution grids. Ultra-fast DC charger, reaching powers of up to 350 kW, have the potential to compromise the stability of AC power grids. To address these challenges, the integration of Distributed Energy Resources (DER), such as energy storage systems (ESS) and renewable energy sources (RES), becomes paramount. Additionally, adopting the smart grid paradigm is crucial for optimizing power flows and addressing the issues related to the inherent randomness affecting the recharge process of EV and the energy production from RESs.

Within this framework, Demo 4 proposes the implementation of an AC microgrid, comprising multi-charger hubs for EV mobility and Energy Services. These hubs incorporate cutting-edge storage systems based on hybrid battery technology, battery swap technology, PV source technology, and a modular AC/DC Smart Micro-Grid architecture. The aim is to offer innovative mobility and energy flexibility services while addressing the challenges associated with EV charging and contributing to the sustainability of the energy infrastructure.

Specifically, the AC microgrid is connected to the LV distribution grid, as illustrated in Fig. 1. It incorporates the following key components:

- 1 **DC Ultrafast-Charging Station**: Battery based ultra-fast charger with a rated at 350 kW.
- 4 **AC Charging Points**: Each with a rated power of 2 x 22 kW.
- 1 **DC Charging Point**: Rated at 15 kW, designed for Vehicle-to-Grid (V2G) functionality.
- 2 **Shelters with PV Roofs**: Each shelter is equipped with a 30 kW photovoltaic (PV) roof.
- 1 **Hybrid Energy Storage System** (HESS): Comprising an NMC battery with a capacity of 150 kWh and LTO battery with an energy of 30kWh.
- **Mobile EV Chargers**: Mobile EV chargers equipped by second life Lithium batteries with a capacity up to 24 kWh, IoT-connected and bi-directional features, Vehicle to Everything (V2X). The Reefilla Fillee is V2X ready, meaning that it can communicate with other vehicles and infrastructure to provide various services, such as Vehicle-to-Grid (V2G) for balancing electricity supply and demand, vehicle-to-vehicle (V2V) for sharing energy with other EV, and vehicle-to-infrastructure (V2I) for powering other devices like streetlights or homes.

This configuration ensures a comprehensive and efficient setup for the AC microgrid, encompassing rapid charging capabilities, distributed AC charging points, V2G functionality, renewable energy generation through PV roofs, and energy storage with the HESS unit.

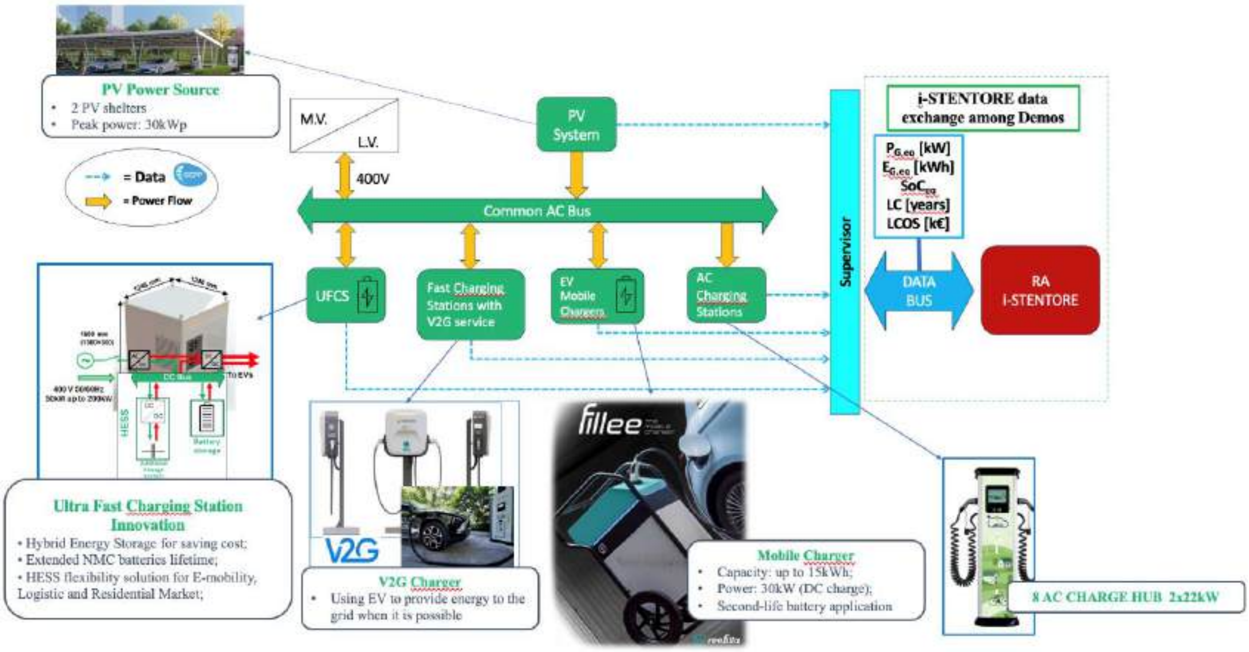


FIGURE 10: SCHEMATIC REPRESENTATION OF DEMO 4 INFRASTRUCTURE.

As shown in Figure 10, to manage the proposed micro-grid the Open Charge Point Protocol (OCPP) will be adopted to manage the following functions:

- Charging point management: OCPP can be used to control the charging process of EV, including starting and stopping the charging session, adjusting the charging power level, and monitoring the charging status.
- Accounting and payment: OCPP can be used to manage charging accounts, including registering users, charging fees, and payment processing.
- Reservation and booking: OCPP can be used to allow users to reserve charging slots in advance, ensuring that they have access to a charger when they need it.
- Monitoring and analytics: OCPP can be used to collect and analyse data from charging stations, such as charging usage patterns, energy consumption, and fault reports.

Here are some specific examples of how OCPP would be used to manage the Multi-Charge Hub:

- When an EV driver connects to a charging point, the OCPP protocol is used to communicate with the back-end system to verify the driver's account and authorize the charging session.
- The OCPP protocol would be used to control the power level of the charger, ensuring that the EV is not charged too quickly and causing damage to the battery.

- The OCPP protocol would be used to send real-time charging data to the back-end system so that the operator can monitor the performance of the charger and identify any potential problems.
- The OCPP protocol would be used to send notifications to the driver when the charging session is complete so that they can unplug the EV and resume their journey.

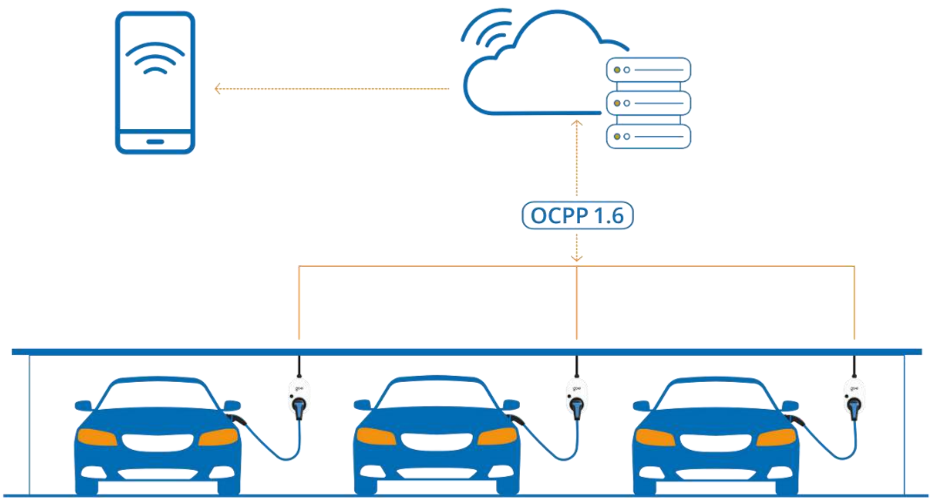


FIGURE 11: CHARGING STATION EQUIPPED WITH OCPP PROTOCOL

By using OCPP, the Multi-Charge Hub can be managed efficiently and securely, providing a seamless charging experience for EV drivers.

5.2 DEMO 4 OBJECTIVES

The primary objective of DEMO 4 is to showcase an integrated and innovative infrastructure that not only supports electric vehicle (EV) charging but also emphasizes energy flexibility services. This includes the incorporation of renewable energy sources, advanced storage solutions, and efficient power management systems. The DEMO will specifically focus on two key aspects:

- **Integration of a hybrid storage system within the ultra-fast charging station**: The pulsing nature of EV recharge, coupled with its randomness, can potentially compromise the stability of the microgrid and the lifespan of existing batteries. Therefore, the implementation of a hybrid storage system aims to counteract sudden variations in power required by EV while simultaneously extending the lifespan of the batteries installed within the charging station.
- **Optimal management of the microgrid using strategies based on optimal power flow algorithms**: The flexibility provided by storage devices and, eventually, the recharge of EVs can be optimally managed through suitable real-time control strategies and offline scheduling operations.

5.3 MAIN INNOVATIONS OF DEMO 4 OF I-STENTORE

The proposed system utilizes an integrated Energy Management System (EMS) to optimize charging processes and extend the lifespan of EV batteries. Here are some of the key innovations in this approach:

- **Smart Charging and Battery Health Monitoring**: The EMS employs advanced algorithms to monitor battery health parameters, such as state of charge (SoC), state of health (SoH), and temperature. This real-time data is used to determine the optimal charging parameters for each battery, ensuring that charging is conducted in a way that minimizes stress and extends battery life.
- **Adaptive Charging Strategies**: The EMS adapts charging strategies based on various factors, including the battery's current state, current weather conditions, and the availability of renewable energy sources. For instance, during periods of high solar production, the EMS may prioritize charging from solar panels to maximize the use of clean energy and reduce reliance on the grid.
- **Battery Balancing and Equalization**: To prevent uneven wear and extend battery life, the EMS implements battery balancing and equalization techniques. These techniques redistribute energy among cells to maintain optimal voltage and capacity balance, reducing the risk of premature aging.
- **Vehicle-to-Grid (V2G) Integration**: The EMS can facilitate Vehicle-to-Grid (V2G) technology, allowing EV batteries to supply electricity back to the grid during periods of peak demand or grid instability. This bidirectional power flow not only benefits the grid but also provides an additional income stream for EV owners.
- **Integration with Renewable Energy Sources:** The EMS can seamlessly integrate with renewable energy sources, such as solar panels and wind turbines. This integration allows the system to prioritize charging from renewable sources, reducing reliance on the grid and promoting sustainability.

By implementing these innovative approaches, the proposed system can effectively extend the lifespan of EV batteries while promoting sustainable energy use and grid stability. The EMS plays a crucial role in managing the charging process, optimizing energy consumption, and protecting battery health, making it a key component of a sustainable and future-proof EV charging infrastructure.

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6 DEMO 5 AGRI-PV FARM WITH ENERGY STORAGE CAPABILITIES BASED ON HYDROGEN AND BESS TECHNOLOGIES OVERVIEW

The i-STENTORE demonstrator 5, in Luxembourg, is a singular application at European level that aims to demonstrate how the optimal selection and design of a Hybrid Energy Storage Systems (HESS) can improve the operation of an agricultural area in synergistic combination with a renewable energy system, namely with on-site photovoltaic generation, i.e. agri-photovoltaics (APV).

The application of the APV concept in the agricultural sector makes it possible to improve use of the land, due to generating electricity from PV panels mounted on solar trackers while still enable an agricultural cultivation. Depending on the design of the APV plant the canopy generated by the solar trackers protects cattle, crops, and land from increasingly frequent extreme weather conditions, providing shade during intense summer heat waves and shelter during intense winter storms, protecting from hail, frost, and drought damage. In addition, APV plants have the potential of high socio-economic impacts contributing to the diversification of farms as they create new business opportunities for farmers, and reciprocally enhancing the land use when compared with classic photovoltaic power plants. At the Luxembourgish demonstrator, sustainable and socially acceptable agricultural concepts will be developed which include innovative measures to improve the micro-climate and increase the biodiversity benefiting from the synergic implementation of the photovoltaic systems. Subsequently, a detailed monitoring system will be implemented in the power plant to monitor the effects on the different processes.

In addition to the APV plant, the hybrid system accounts with the combination of a wind turbine installed in the vicinity of the plant, which is expected to provide a complementary energy generation, minimising the intermittency of power generation of both technologies, creating a smoother profile, and increasing the reliability of the power system.

On the energy storage side, the Luxembourg demonstrator combines two additional energy storage systems to increase the plant's energy flexibility, optimizing the use of the renewable energy produced and improving the plant's interaction with the electricity grid by potentially providing ancillary and flexibility services to the grid operator. The hybrid energy storage system consists of two different technologies, a large-scale electrolyser, and a grid-forming utility-scale BESS. The hydrogen produced by the electrolyser will be stored in trailers tanks and transported over short distances to industrial consumers. The BESS with grid-forming functionalities will support the interaction with all other energy assets in the APV farm, through a hierarchical operational and control system (HOCS) specifically adapted and parametrized for controlling the dynamics of APV plant response. The innovative HOCS uses the same standard communication protocols as phasor measurement units, enabling the system for Virtual Synchronous Synchronized Control (VSSC) of optimum bi-directional power flows of the APV plant, resulting in increased flexibility which will enhance the plant electrical performance and the energy exchanges with the power grid.

6.1 DEMO 5 TECHNOLOGICAL ASSETS AND CONFIGURATION

Demo5 is located in a rural area of Luxembourg, belonging to the township of Kielen. Here, the agricultural activity-related energy processes of an Agri-photovoltaic (APV) plant are combined with high-performance energy processes provided by the hybrid energy storage system. The system is composed by the following assets:

- On the production side, the hybrid renewable energy system is composed by:
  - A Wind turbine of **4,2 MW_p** with an estimated annual yield **> 10 GWh**
  - A photovoltaic power plant divided in two sectors, totalizing **2.4 MW_p**, with an estimated annual yield **> 3.7 GWh**

- The hybridized energy storage systems, is on its hand composed by:
  - A proton exchange membrane for "Green hydrogen" production with a rated stack power: **2.5 MWel,** combined with a storage tank of 115 **m^3** and a trailer filling station at 380 bar
  - A utility-scale Li-Ion BESS with grid-forming capabilities, with a rated capacity **of 500kWh** at **1MW** Safe cathode materials (Nano-LiFePO 4)

Figure 12 conceptualizes the demo 5 system. Production assets, storage and electrolyser, are connect to a private, on-site MV grid, behind the DSO meter, connecting the grid in a single point. All the electricity demand inside the local MV grid should be satisfied by the system, and only surplus will be injected into the public grid.

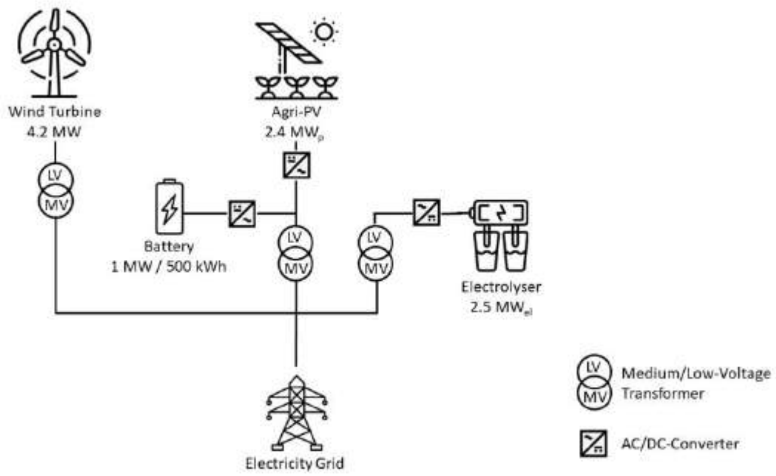

FIGURE 12: CONCEPTUAL DIAGRAM OF THE HYBRID ENERGY STORAGE SYSTEM OVERVIEW OF DEMO 5.

The storage capacity operation will be optimized to minimize wind power curtailment and to profit from the predictability of solar PV production for peak-shaving and load balancing, while meeting the H_2 throughput.

6.2 DEMO 5 OBJECTIVES

Demo 5 aims to demonstrate 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. The flexibility offered by the large energy storage capacity will not only improve the energy performance of the APV plant, but also other processes related to the plant's crops, microclimate, and biodiversity and potentially improve the grid reliability and power quality by providing flexibility and ancillary services to the grid operator. Furthermore, it is planned to explore hydrogen not only from the storage flexibility management side perspective but also as market vector by providing this commodity to local industry, which will contribute to demonstrate how storage systems can improve APVs plant business cases.

To optimize energy generation and exploitation of the system according to multi-objective principles numerical models to simulate all the assets and interactions of the plant under generic operating conditions will be developed while taking into account the potential degrees of freedom offered by energy storage systems. By integrating the BESS, it will be possible to optimize the energy exchanges with the power grid to minimize the cost of the energy consumed by the plant and maximize the profit on trading energy surpluses. Furthermore, the BESS with grid-forming capabilities will provide new functionalities to the APV system and potentially offer new services to the grid operator. In this manner, in addition to conventional grid frequency and voltage regulation services, which are particularly important in low density rural grids, this grid-forming BESS will be ready to offer to the system operator other advanced services such as inertia emulation, power oscillation damping, improved stability/passivity for the active system, improved power quality and even the ability to energize the system after a blackout (black-start), among others.

6.3 MAIN INNOVATIONS OF DEMO 5 OF I-STENTORE

In this demonstrator, an innovative hierarchical operational and control system (HOCS) will be deployed for controlling the dynamics of the APV plant. The digital hierarchical control will act as synchronization system for the active assets of the pilot, such as the BESS, using the same standard communication protocols form communicating with the Phase measurements units in the grid. Such innovative synchronization system will allow implementing a virtually synchronous synchronized controller (VSSC) for the BESS. In addition, the Smart Grid Architecture Model (SGAM) will be extended by including a new 'Cluster' control layer to coordinate the real-time operation of multiple stations interconnected within a given area of the power grid. In this sense, a cluster-level controller will be implemented to regulate in real time the collaborative response of multiple distributed resources according to the signals received by a wide-area measurement system (mainly formed by PMU and RTUs), improving stability and robustness. Moreover, the SGAM interoperability layers will be revised to properly organize the functionalities and relationships establishing edge-, fog- and cloud-computation tiers, to adapt to the taxonomy and ontology of the active energy and storage assets and actors participating in the energy systems, in general.

A digital platform for managing energy and services will made available for the specificities of the demonstrator, bringing several levels of interoperability and intelligence to the APV plant, including new functionalities and services addressed to facilitate the plant energy management and to assist operators in decision making processes. This digital platform will cover the high layers of the SGAM and will allow APV plant operators monitoring and analysing processes, and making decisions regarding rational use of energy, utility products/tariffs contracting, performance improvement, and new assets investment. To this end, the digital platform will offer user-friendly interfaces as well as a set of intelligent management tools for planning, operating, analysing, accounting and administrating energy generation, consumption, and storage in the APV plant. The intelligent tools of the digital platform will allow optimizing the plant's energy use and the impact on the rest of agricultural and bioclimatic processes. From an energy point of view, these intelligent tools will allow minimizing the APV plant's energy costs and generating new income streams by optimally managing the interactions with external markets (energy, hydrogen). In addition, the digital platform will securely manage the APV farm data space and will implement the necessary mechanisms to interoperate with other platforms and dataspaces, which is the case of i-STENTORE common data governance middleware layers.

7 CONCLUSIONS

This deliverable is the 1st part of 3 consecutive and evolving deliverables that aim at describing the evolution on the technology/services/assets deployment in the various i-STENTORE demonstrations.

The comprehensive analysis provided in this report of the i-STENTORE project pilots demonstrates a strong effort of all the project partners towards technological advancement and hybridization in energy storage systems. Each of the five distinct demonstrators outlined in the report displays innovative approaches to addressing the challenges of renewable energy integration and grid management. From leveraging molten glass for thermal storage to exploring the potential of "Green hydrogen," the project ambitiously tackles various challenges of energy storage and optimal utilization.

The document highlights the various technological assets employed in each demo and explains their specific objectives and main innovations, highlighting the project's effort to improve energy storage capabilities. Furthermore, the emphasis on ancillary services provision and grid support shows the project pilots' broader goals of not just technological innovation but also economic viability and grid stability.

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