Batteries Europe

Position paper

Hybridisation Task Force

April 2024

In cooperation with

BEPA Batteries European Partnership Association

ACKNOWLEDGEMENT

Batteries Europe Secretariat is an EU-funded project that has received funding from the European Union’s Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676.

DISCLAIMER

The current publication constitutes a short and preliminary version of the position paper. The final and more extensive version will be published in Q4 of 2024.

Batteries Europe Task Force Hybridisation

Interim Chair:	Peter Fischer (Fraunhofer ICT)
Co-Chair:	Prasanth Venugopal (U.Twente)
Technical coordinator:	Edel Sheridan (SINTEF Energy)
Lead authors:	Peter Fischer (Fraunhofer ICT), Prasanth Venugopal (U.Twente), Laurent Garnier (CEA), Franco Di Persio (CIRCE), Mattia Duranti (Fondazione Bruno Kessler-SE)
Contributing authors:	Pablo Fontela Martinez (ENEL), Pénélope Nabet (EIT InnoEnergy), Pilar Meneses (Cidetec Energy Storage),
Task Force members:	Alfonso Bello Bocio (EURECAT), Ákos Dervalics (InnoEnergy), Iosu Cendoya (CIDETEC), Daria Giovannacci (Geyser Batteries Oy), Ari Hentunen (VTT), Wouter Ijzermans (BEPA), Manuel Baumann (KIT), Janik Fernandez (Clean Aviation Joint Undertaking), Stefano Passerini (KIT), Luis de Prada (EUCAR), Luca Barattini (GES - Green Energy Storage s.r.l.), Erwin Marckx (EUROBAT), Edoardo Gino Macchi (Center SE at Fondazione Bruno Kessler), Massimiliano Maurizio De Benedetti (Enel X Inn & Prod Lab), Vito Di Noto (Università degli Studi di Padova), Rudy Pastuzak (Dassault Systèmes), Roberto Scipioni (Sintef Energy), Steffen Spieler (Tofwerk AG), Philippe Stevens (EDF), Khiem Trad (VITO), Luis Trilla (IREC), Yaolin Xu (HZB), Franz Schwarz (SGL Carbon), Maher Chebbo (CTECHNOLOGYS)

Acknowledgements: We would like to thank Spyridon Pantelis (EERA) for the overall coordination of the Task Forces, Alessandro Romanello (EIT InnoEnergy) as coordinator of Batteries Europe, and the BEPA Secretariat for their support in the operation of the Task Force. Special thanks to Fatima Ahmed, Adeola Adeoti, Lucia Sardone (CLERENS), and Maria Luisa Fernandez Vanoni (EERA) for editorial support. We would also like to acknowledge the inputs and considerations from the European Commission, the Batteries Europe Secretariat and Batteries Europe Advisory Board. This position paper has been drafted in collaboration with the StoRIES project.

Executive Summary

In the EU Commission's Recommendations on Energy Storage in 2023, it is proposed member states continue to invest in research and innovation on energy storage, specifically on topics like long-term storage, hybrid storage solutions, behind the meter solutions for customers and the utilisation of electricity stored in electric vehicles batteries for grid purposes, i.e. Vehicle to Grid (V2G). Batteries Europe in autumn 2023 initiated a Task Force with a focus on Hybridisation of energy storage systems for both stationary storage and transport applications. This group is also following up on some areas that fall in between the topics of the Working Groups and other Task Forces (TF) which are relevant to the battery research community, such as the V2G concept.

This position paper is a first version of the efforts of the Batteries Europe TF hybridisation. In chapter 1 and 2, it determines what hybridisation is and why in some cases, it may provide an optimal solution for energy storage. Chapter 3 covers a very brief, non-exhaustive description of technologies which can be used in hybridisation. Chapter 4 gives details of research topics which are necessary to enable all energy hybridisation solutions, including research on power electronics, hardware for communication and sensing, tools and digital twins for simulation and software to address hierarchical dynamic energy management systems. In addition, work is needed to develop solid business cases for hybrid energy storage solutions (HESS). Furthermore, it is key we take lessons learned from past projects, which leaves a need for a mechanism to provide such an overview of research projects and results.

Chapter 5 covers a series of case studies and identifies the research needs within these selected cases of hybridised stationary energy storage. These cases include both in-front-of-the meter and behind-the-meter examples addressing topics including, combining long and short duration storage solutions, large scale and micro-grid assisted UPS (Uninterrupted power supply) solutions, hybrid energy storage solutions for energy islands, momentary reserve with RES (Renewable Energy sources), hybrid energy storage solutions for deferral of grid investments and the Grid booster, a CAPEX deferral phase.

In addition, the TF investigated cases including single-family homes (<50kWh/day) - Utilising batteries and heat storage options to achieve better efficiencies and hybrid battery systems as neighbourhood batteries. While Vehicle to Home (V2H) and Vehicle to Grid (V2G), may not be seen strictly viewed as a hybridised systems the TF chose to include this in their analysis as it was a topic which is often neglected as it sits between domains of competence and technologies. Chapter 6 takes a brief look into the needs for hybridisation in both the waterborne and aviation sectors while Chapter 7 examines the need for hybridisation in charging (refuelling) infrastructure.

The above chapters provide an initial view of a key selection of topics and their research needs, however within is not included a set of KPIs (Key Performance Indications) and indeed is not an exhaustive list of the topics which need research for hybridisation of energy storage systems. Chapter 8 addresses some of the policy issues around hybridisation while Chapter 9 provides key recommendations to researchers, the European Commission, national and regional authorities and policy makers alike.

It is the hope of the Task Force on Hybridisation that this position paper will provide a solid starting point to develop policy and research around hybridised energy storage solutions which can result in significant benefits regarding cost, performance, flexibility, extended lifetime, improved reliability, energy security and sustainability.

CONTENTS

1 INTRODUCTION ... 8
  1.1 Why can Hybridisation of energy storage provide an important solution? ... 9
  1.2 What are the thematic boundaries of this Task Force? ... 10
2 DEFINING HYBRIDISATION ... 11
  2.1 Traditional hybridisation ... 11
  2.2 "Internal hybridisation" ... 11
3 STATE OF ART TECHNOLOGIES DEFINITIONS ... 12
  3.1 Electrochemical storage devices ... 12
    3.1.1 Supercapacitors ... 12
    3.1.2 Li ion batteries ... 12
    3.1.3 Sodium-ion batteries ... 13
    3.1.4 High temperature batteries ... 13
    3.1.5 Redox flow batteries ... 13
    3.1.6 Lead acid batteries ... 13
  3.2 Chemical storage devices ... 14
    3.2.1 Hydrogen storage using Fuel cells ... 14
  3.3 Thermal storage devices ... 14
    3.3.1 Thermal storage using Heat pumps ... 14
4 RESEARCH TOPICS COMMON TO HYBRID ENERGY STORAGE SYSTEMS ... 15
  4.1 Efficiency and flexibility of power electronics ... 15
  4.2 Hardware for Communication and Sensing for Energy Management System ... 15
  4.3 Tools and Digital Twins for simulation of hybrid energy storage systems ... 16
  4.4 Software to address a hierarchical dynamic Energy Management System ... 17
  4.5 Business cases for hybrid energy storage solutions (HESS) ... 18
  4.6 Overview of research projects and results ... 18
5 CASE STUDIES AND IDENTIFICATION OF RESEARCH NEEDS FOR HYBRIDISED STATIONARY ENERGY STORAGE ... 20
  5.1 Combining Long and Short duration storage solutions ... 20
  5.2 Large scale and micro-grid assisted UPS solutions for critical infrastructure ... 21
  5.3 Hybrid energy storage solutions for energy islands ... 22
  5.4 Momentary reserve with RES ... 23
  5.5 Hybrid energy storage solutions for deferral of grid investments ... 25
  5.6 Grid booster – CAPEX deferral phase ... 26

5.7 Single-family homes (<50kWh/day) - Utilising batteries and heat storage options to achieve better efficiencies of battery systems 27
5.8 Vehicle to Home (V2H) and Vehicle to Grid (V2G) 27
5.9 Neighbourhood batteries / high power with high energy 28
6 CASE STUDIES FOR HYBRIDISATION OF ENERGY STORAGE IN TRANSPORT 30
6.1 Waterborne 30
6.2 Aviation – Hybridisation for light duty & heavy duty aircraft 31
7 CASE STUDIES FOR HYBRID ENERGY STORAGE RELATED TO CHARGING INFRASTRUCTURE 34
7.1 Hybrid refuelling-recharging infrastructure and hubs 34
7.2 Charging Infrastructure – The Electric Road 35
8 POLICY IMPLICATIONS 36
9 RECOMMENDATIONS AND CONCLUSIONS 39
10 REFERENCES 40
ANNEX A - LIST OF SELECTED PROJECTS 42

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

ABBREVIATIONS AND ACRONYMS

Abbreviation	**Definition**
AC	Alternating Current
BE	Batteries Europe
BEPA	Batteries European Partnership Association
BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	Capital Expenditure
DC	Direct Current
EMS	Energy Management System
ESS	Energy Storage Systems
ETIP	European Technology and Innovation Platform
EV	Electric Vehicle
HESS	Hybridisation of Energy Storage Solutions
HVDC	High voltage direct current
ICE	Internal Combustion Engines
kHz	Kilohertz
LFP	Lithium ferrophosphate
LIBs	Lithium-ion batteries
LiCoO2	Lithium cobalt oxide
LTO	Lithium titanium oxide
MW	Megawatts
MWh	megawatt hour
NAS	High Temperature Sulphur Batteries
NCA	Lithium nickel cobalt aluminum oxide
NMC	Lithium nickel manganese cobalt oxide
OEM	Original Equipment Manufacturer
OPEX	OPerational EXpenditure
PCS	Power Conversion System
PEM	Proton-exchange membrane
RES	Renewable Energy Systems
RFB	Redox flow batteries
RUL	Remaining Useful Life
SAF	Sustainable Aviation Fuels
SIBs	Sodium-ion batteries
SoC	System on Chip
SoH	State of Health
SRIA	Strategic Research and Innovation Agenda
TCO	Total cost of ownership
UPS	Uninterruptible Power Supplies
V2G	Vehicle-to-grid
V2H	Vehicle-to-Home
WG	Working Group

1 INTRODUCTION

The REPowerEU plan[1] put forward by the European Commission in 2022 includes a considerable acceleration in the roll-out of renewable energy which in turn will put a greater demand on stationary storage solutions as well as carbon neutral mobility solutions for all sectors of transport. Batteries offer excellent efficiency and from this point of view are a key asset to the development of the energy grid as well as charging infrastructure. However, in cases when consider a holistic stationary storage system that can offer both power and energy storage capabilities it may be worth considering a hybridised system.

In the EU Commission's Recommendations on Energy Storage 2023,[2] it is proposed member states continue to invest in research and innovation on energy storage, specifically on topics like long-term storage, hybrid storage solutions, behind the meter solutions for customers and the utilisation of electricity stored in electric vehicles batteries for grid purposes, i.e. Vehicle to Grid (V2G). Batteries Europe has on its part, initiated the development of a Task Force with a focus on Hybridisation of energy storage systems for both stationary storage and transport applications. This group is also following up on some areas that fall in between the topics of the Working Groups and Task Forces which are relevant to the battery research community, such as the V2G concept.

Traditional hybridisation can be defined as combination of two complementary storage systems to result in a beneficial situation for the energy storage requirements case. The task force collected the viewpoint of Batteries Europe experts, suggesting the necessary improvements, which have to be made to enable hybridised systems by battery research. The projected benefits for such hybrid solutions are an increase in performance, reliability, lifetime and safety as well as a decrease in storage system costs. To activate such gains, further advancements in the battery or energy management system needs to be made to facilitate optimal use in the selected hybridised application.

1.1 Why can Hybridisation of energy storage provide an important solution?

Hybridisation takes advantages of different storage systems and combine these together to create a application-relevant solution which may have greater reliability, durability, flexibility and better sustainability, leading potentially to lower costs. However, traditional hybridisation also comes with a greater initial investment cost of connecting the two solutions physically and this too can bring additional complexity. In order to take advantage of the hybridised system, a good analysis of the balance of plant calculation is required for the specific case before installation. While it is not in the remit of this publication to investigate or determine the balance of plant, it is an important aspect to consider when implementing a hybridised system. In section 2 of this document, we take a deeper look at our definition of hybridisation, while in section 3 we provide a very brief description of technologies most commonly used in hybridised systems, to enable readers not familiar with such technologies.

In section 4, we firstly address some of the research needs which are common to all areas of hybridisation including development of power electronics, sensors and communications for HESS, software tools and digital twins, and the need to develop a network to ensure lessons are learned from earlier projects.

Following this, in section 5, 6 and 7 we address specific cases where hybridisation can be used in stationary storage, transport applications and within the charging infrastructure. While this is not a complete overview of the research needs for the hybridisation sector, it should provide the reader with an understanding of the scope of topics which need to be addressed.

In addition, section 8 addresses the policy aspects within Europe that are important to consider as these have a large impact on driving the business case towards using the optimal hybridised energy storage solutions with regards to Environmental, Governance and Societal concerns. This is particularly relevant in the case of stationary energy storge solutions and the ownership and operations of the energy storage assets. In addition, the development of standards for charging and refuelling both hybrid and non-hybridised solutions for road, heavy duty transport, waterborne and aviation will be essential to facilitate the growth of the industry as a whole. Without standardised solutions large scale roll out will not be possible.

In the appendix can be found an overview of some of the many projects the task for contributors have been involved in are highlighted. This aims to provide an understanding of what areas have been investigated and what remains to be done.

This position paper is aimed to provide a brief overview of some selected research areas and to address policy changes required in order to prepare the ground for large scale implementation of hybrid energy storage systems to support both the energy and transport sectors. These suggestions are considered with the European Commission and Member States representatives, policymakers, industry & start-up companies (including energy companies, maritime and aviation companies), the research community and associations & communities in mind with the goal to assess and propose key strategic research areas. The information herein may be used to support decisions regarding research to be carried out within future programs such as the European Commission's framework programs, EIC program, national and regional research programs etc. Of equal importance it is hoped to be a starting point for discussion concerning policy regarding hybridised energy storage.

1.2 What are the thematic boundaries of this Task Force?

The task force on Hybridisation of energy storage solutions (HESS) is new within Batteries Europe and was established in autumn 2023. It facilitates the collaboration of experts from several sectors including stationary storage, aviation and waterborne technology who have worked with battery technology. The Task Force has also been collaborating with the StoRIES project, having a wider scope that addresses hybridisation of various types of energy storage. While there are a lot of hybridised energy storage solutions which can be investigated our focus in this publication will be on hybridised technology combined with battery-based solutions. Herein is an initial view identifying topics which require research to enable wide scale implementation of HESS. However, prior to wide scale publication an extensive consultation process on KPIs is necessary with the WG5 (Implementation of batteries in transport sector) and WG6 (Implementation of batteries in stationary storage sector) and with stakeholders beyond Batteries Europe.

2 DEFINING HYBRIDISATION

2.1 Traditional hybridisation

In traditional hybridisation two or more different energy storage systems are combined to provide a benefit to the chosen application. The benefit of these combinations can include lower costs, improved performance, extended lifetime, improved reliability, greater sustainability or reduced emissions.

Therefore, this type of hybridization is often referred to as “hybridisation on system level”. While each of the unique energy storage systems has its own unit management system (such as a BMS), these need to be connected and combined to facilitate the use of both systems conjointly. Hybridization can be linked physically on a common DC or AC-bus or virtual just via a data link. The conjoined energy system control is referred to as the Energy Management System (EMS) through this document. An EMS is essential and is a digitally driven solution with converters.

Heterogeneous battery system – This is a specific type of traditional “external” hybridisation in which a system that uses two different types of batteries to provide different functionality to a single energy system. Several examples can be found in the maritime sector where one type of battery supplies power and the other supplies energy to a vessel. Another example is the case of stationary storage island in which grid flow (Li-ion battery system and Lead acid battery) energy and back up.

Micro-hybridisation is a term used in some industries such as aviation. This describes the situation where functions which have lower energy demands are provided for by a smaller energy storage form such as batteries, while the main energy system such as the engine is run on a different technology. For example, an aircraft may have its propulsion run on Sustainable Aviation fuel (SAF), however all or part of the auxiliary systems such as air-conditioning, landing gear control etc. may be run on batteries.

2.2 “Internal hybridisation”

This is a system that truly hybridises two or more concepts in a single system. A few examples exist which are composed of either a chemically or physically combination of two or more systems resulting in an entirely new technology which we will refer to as Internal hybrids. Examples of internal hybrids include, Powercaps which are a cross between batteries and supercapacitors and the Battrolyser which is a cross between a fuel cell and battery. In this position paper we have not covered internal hybridised systems.

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

3 STATE OF ART TECHNOLOGIES DEFINITIONS

Herein we provide an overview of the most commonly used energy storage systems which are combined as a part of HESS. There are several means of energy storage, including electrical, chemical, thermal and mechanical some of which are not mentioned herein. These include Nickel based batteries (electrochemical), Carnot batteries (thermal), flywheels and compressed air (mechanical).

3.1 Electrochemical storage devices

3.1.1 Supercapacitors

Supercapacitors, also known as ultracapacitors, store electrical energy through the physical separation of charge within an electrolyte solution using high-surface-area electrodes to achieve high capacitance. The electrodes are typically made from activated carbon or other porous materials with high surface areas, allowing for efficient adsorption of ions. Supercapacitors have high power densities from 1,000 even up to 20,000 watts per kilogram (W/kg) and fast charge-discharge rates but low energy density, typically a maximum of 10 (Wh/kg).

3.1.2 Li ion batteries

Li ion batteries refer to a family of Li ion-based battery chemistries and typically have energy density ranging between 150 to 300 (Wh/kg). In general, most variations are seen in the cathode material and electrolyte used, which result typically in the battery having different characteristics mostly based on the cost and performance. These various battery chemistries are described in the roadmaps of Batteries Europe.

High power Li-ion batteries – Li-ion batteries can specifically be designed to provide high power with power density of for example up to 10,000 (Wh/kg) however this comes with a significant trade off on the energy density of the battery. The use of anodes with lithium titanate (LTO) or incorporation of silicon in graphite anodes along with the use of cathode materials consisting of lithium iron phosphate (LFP) or lithium nickel cobalt aluminum oxide (NCA) are commonly used for high-power applications.

High energy Li-ion batteries – Likewise Li-ion batteries can be designed specifically to provide high energy but in turn the power density may be sacrificed. Theses typically employ Lithium cobalt oxide (LiCoO2) or Lithium nickel manganese cobalt oxide (NMC) as cathode material and can provide an energy density even up to even 300 (Wh/kg.)

3.1.3 Sodium-ion batteries

Sodium-ion batteries (SIBs) are a type of rechargeable battery that utilizes sodium ions (Na^+) as the charge carriers and typically has an energy density which ranges from between 100 to 150 watt-hours per kilogram (Wh/kg). Similar to lithium-ion batteries (LIBs), they consist of cathodes, anodes, and electrolytes. However, in SIBs, sodium ions shuttle between the cathode and anode during charge and discharge cycles, rather than lithium ions.

3.1.4 High temperature batteries

High temperature batteries operate within a temperature window from 120C up to 350C and can offer both high energy density with high power density. However, due to the elevated temperature of operation they are generally most suited for stationary storage applications. Zebra batteries based on Sodium-Nickel Chloride are one such example and operate with a liquid sodium negative electrode separated from the positive electrode by a B-alumina solid electrolyte. Sodium-sulphur is another example which operates between 300C-350C. While such batteries exhibit many advantages their main drawback is the requirement to continuously operate as if they become cold the electrodes will no longer operate.

3.1.5 Redox flow batteries

Unlike cell-based systems, the electrochemical conversion in redox flow batteries (RFB) happens in a continuous electrochemical reactor. This means, that the energy storage medium is fed as a fluid to the cell and after conversion the fluids are collected in a reservoir/ tank. The fluid is regenerated upon charging of the system. In a typical technical RFB, a two-tank design is used. The electrolytes are pumped in two electrolyte circuits, one for the minus-pole reaction (negolyte) and one for the plus-pole reaction (posilyte). The cells in a technical system are usually arranged in stacks, in a design like the one of a fuel cell system. The main advantage of a flow battery are the individual scalability of energy (electrolyte volume) and power (electrode area/ number of cells in a stack), as well as high storage efficiency and service life. Most applied technology is the all-vanadium redox flow battery, which utilise acidic vanadium sulphate solutions as energy storage medium (23Wh/L). Typical energy density of electrolytes is between 10 to 30 Wh/L., with some batteries like Zinc Bromine RFB can go up to 80Wh/L. Available installations range from 2 to 100,000 kW [3].

3.1.6 Lead acid batteries

Lead-acid batteries are a type of rechargeable battery that utilises a chemical reaction between lead dioxide (PbO_2) and metallic lead (Pb) in an aqueous sulfuric acid (H_2SO_4) electrolyte to generate electrical energy, typically with an energy density of 30-40 Wh/kg. They have been traditionally used in automotive applications (e.g., SLI = starting, lighting, and ignition), backup power systems, uninterruptible power supplies (UPS), and stationary energy storage applications. Sealed lead-acid batteries or valve regulation lead acid batteries utilise gel electrolyte. These batteries are generally maintenance free and safe however they are more expensive that tradition lead acid batteries are also require a specific charging profile to prevent overcharging.

3.2 Chemical storage devices

3.2.1 Hydrogen storage using Fuel cells

Fuel cells utilise hydrogen to produce electricity and can be used in a wide variety of applications. Unlike batteries, they do not discharge, but produce power for as long as hydrogen (or liquid ammonia) fuel is available. They are more efficient than standard internal combustion engines (ICE) but are considerably less efficient than batteries. Fuel Cells are considered useful for providing the baseload, however they do not withstand sudden changes in the energy demand which causes considerable degradation to the fuel cell system in particular to the membrane.

3.3 Thermal storage devices

3.3.1 Thermal storage using Heat pumps

Heat pumps are energy efficient devices that transfer heat from one site to another. By using a small amount of energy, they can either act as heating or cooling systems depending on the needs of the user. There are three types of heat pumps, based on where they draw the heat from: air-source heat pumps, ground-source heat pumps (geothermal) and water-source heat pumps. Heat pumps have become more and more popular in the past years and are widely used in residential, commercial and industrial settings for their ability to maintain comfortable indoor temperatures and for their low environmental impact.

4 RESEARCH TOPICS COMMON TO HYBRID ENERGY STORAGE SYSTEMS

4.1 Efficiency and flexibility of power electronics

Power converters are a key component for operating electrical energy storage systems. For hybrid battery systems Power Conversion System (PCS) solutions are currently not optimised and standard inverters are used for each battery type, these inverters are then coupled at their AC side. Novel PCS solutions are necessary to reduce costs and provide modularity, flexibility and resilience to the hybrid BESS.

The optimal battery combination (Heterogeneous battery system) in a given hybrid BESS may include batteries with different voltage levels and peak power capability which adds a layer of complexity in the definition of these novel PCS, in particular if the intention is to avoid oversizing the PCS. Some potential solutions are explored at research level and need to be further developed to reach market applications. Some of these PCS can bring novelty at architecture, topology or control levels, examples of novel PCS are:

- ***Multiport power converters***: Ideal for modular solutions, can incorporate several battery systems with reduced cost. Battery voltage must be within a given range but are very flexible in the power management side.
- ***Multi-level power converters:*** Very flexible in terms of battery voltage range but extension of lifetime using multiple electrochemical systems with power electric systems optimised for extension of lifetime adds complexity to the control. Some limitations are encountered in terms of power management flexibility.
- ***Fault tolerant power converters***: Can increase costs slightly but ensure that the battery remains in operation when the converter has an internal failure.

Research needs:

- Optimisation and Demonstration of Power Converters with multiple electrochemical power systems which provide different voltage levels, peak power capacity and within different safety margins.
- Development of power control software for use on multiple hybridised units.

4.2 Hardware for Communication and Sensing for Energy Management System

Sensors can provide a host of information about the state of health (SoH) of energy storage systems such as batteries and fuel cells. These sensors need to be integrated in the energy storage system such as the battery and the information must be collected in real time. The correlation of this information for both components in a HESS can provide an overview of the overall SoH and provide the potential to calculation of optimal usage in order to promote longevity of the HESS.

There are activities and projects that have been suggested and followed by Battery 2030+[4] and promoted by Batteries Europe, to develop sensors for battery systems and these can be taken with similar approached to fuel cells and other energy storage systems. The key here is to combine the information from both energy storage systems in the HESS, in real time, to calculate an overview of the SoH of the system and provide real time feedback to the optimal operation of the HESS.

Research needs:

- Development of new types of SoC/SoH sensors, especially SoH sensors to allow to quantify the boundary conditions of stable operations vs demanding operation.
- Development of new digital tools, which could replace classical sensors by machine learning/AI-techniques or genetic algorithms to allow the complex analysis of existing BMS data.
- New lifetime models, which helps to predict best-case operations.
- All the results of the first three points should help to develop control strategies for operation with minimum-wear for the combined storage solutions in the HESS or tools to define the optimum layout and dimensioning of both storage solutions.

4.3 Tools and Digital Twins for simulation of hybrid energy storage systems

Due to the complex interaction of two or more storage systems, digital twins and real-time modelling can help to model interactions of fast control demand or demanding load situations. If two or more storage solutions are combined on a common DC-intermittent circuit, it can be especially beneficial for the understanding of such systems, when the load operations of the system can be monitored on all time scales up to kHz range (below the time-constant of the 50Hz sinewave). This models then should allow to evaluate control strategies for short and ultrashort duration control like allowing momentary reserve, preventing inclined load situation or just fast frequency control. Other applications, where real-time modelling can be beneficial, are steep power ramps, high ripple currents in the DC circuit or monitoring of oscillations on non-grounded DC-circuits.

Complementary the damage of short-duration operation of a lot of batteries has not been investigated in detail, e.g., effects of ripple currents on RFB or steep load ramps on high temperature batteries.

A more detailed view on modelling of battery storage can be found in the position paper of the Task Force Digitalisation.

Research needs:

- New real-life models of hybrid energy storage up to kHz time domain
- Investigations on effects of short current fanks or ripple currents on BESS
- The two beforementioned points should be used to investigate benefits of HESS operation regards to lifetime.

4.4 Software to address a hierarchical dynamic Energy Management System

DC-DC architectures for intermittent circuits are derived from various applications, each with its unique characteristics:

1. Battery-based DC architectures:

- Small-scale (<1kW): These include battery-based UPS solutions for small devices. They typically use lead-acid batteries or LIB and operate at voltages like 48V.
- Electric vehicles: LIB batteries are commonly used on a 200-360V DC circuit, with a trend towards higher voltages like 500-1000V for better fast-charging compatibility.
- Electrical circuits on large ships: These applications involve long floating DC cables, often combined with Nickel-based batteries.

2. Non-battery based DC architectures:

- Solar strings: These are often connected at 400V or sometimes 600V DC levels.
- Large-scale (1-8MW): Wind turbine architectures commonly utilize >1000V DC, usually floating, as the cables are kept short in the tower head.
- Super large-scale (several MW to GW): These are HGÜ connections of transmission grids.

These diverse architectures serve as blueprints for HESS developments. Wind turbine development, particularly for high voltage components above 1000V, has driven the innovation of new components. However, there is a gap for components in the range of 400V, 600V, or 800V. There is a high demand for switches and SF6-free arc protectors. The future holds the potential for affordable new components from electric vehicle development, which would also benefit DC-connected HESS development.

Research needs:

- For optimisation of HESS solutions, new components for DC, especially safe and SF6-free switches, fused or non-fused disconnectors/ contactors would be highly beneficial.
- Solid-state DC circuit breakers for fast and quick DC current and arc extinguishers.
- In addition, standardisation of DC-levels would help component manufacturers to allow a better variety of components.

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

4.5 Business cases for hybrid energy storage solutions (HESS)

A sustainable business model is required for all hybrid energy storage systems (HESS) which are installed. Research is needed to investigate the value creation case that the energy storage may deliver to its owner and to fully understand the market, policy and regulatory boundaries. All three factors are evolving as more renewable energy sources are introduced into the energy systems. In addition, software which optimises projects to ensure an economically and sustainable business case will be necessary. For the case of stationary storage, the concept of stacking services for energy providers has the potential to lead to more profitable business models, however both policy and regulatory considerations will affect this business case. Although business cases will have to be specifically developed for each case, collaborations between researchers, industry and regulators along with utilities will be necessary in the future to ensure both economic and sustainable driving forces work hand in hand.

Research needs:

- The development of software which optimises projects to ensure an economically and sustainable business case will be necessary.
- The development of business cases which considers both the positive and negative effect and profitability for stacking of services for all stakeholders involved.
- Examine the sustainability aspects of business cases involving hybridised energy storage solutions

4.6 Overview of research projects and results

There have been many national and European framework projects which either have been completed or are currently running concerning development, testing and demonstration of HESS, a taste of which is provided in the ANNEX 1. to this document. However, there is not a specific network or alliance focused on hybrid energy storage research within Europe and the results generated through projects are not correlated. Coordination of research activities can result in shared information concerning the HESS system and subsystem design informing sizing, technical performance, lifetime estimation and financial performance. With such a wide varied of data available from earlier and current research projects along with advancements in computation methods these results could be developed and utilised in a better way.

Due to the lack of assembly of project results, the lessons learned within project are often missed by researchers and industry stakeholders across Europe. A suggestion could be to extend a currently existing networks on energy systems to incorporate a group with focus on HESS. However it should be noted that there are areas which need hybridisation in the transport sector as well. An alternative could be to extend a current project on HESS which covers both the stationary storage and transport sectors to become a network beyond the lifetime of the project.

Research needs:

- Support the development of a lasting network of researchers, industry, member states and EU commission which will collect and correlate data from past and existing projects to ensure sharing of the lessons learned. This community could also serve to provide guidelines for decisions of industry and policy makers developing the European energy and transport systems.

5 CASE STUDIES AND IDENTIFICATION OF RESEARCH NEEDS FOR HYBRIDISED STATIONARY ENERGY STORAGE

5.1 Combining Long and Short duration storage solutions

The terms “long- and short-term energy storage” are highly dependent on the system requirements and application. In battery technology, long term storage capacity is currently considered to be above ca 12 hours with negligible decay of energy density. Redox flow batteries are considered for long-term energy storage. However, in regard to a pumped hydro power plant, long-term energy storage can refer to storing energy for several weeks or even months. The installation of long-term energy storage facilities is also highly dependent on the space, climate and landscape available.

Short-term energy storage demands can place a huge demand on any single energy storage system and may result in premature breakdown. This is the case with fuel cells which are found to experience significant ageing upon rapid peak energy demands, however they excel in providing a stable baseload. Both Li-ion batteries and Li-ion capacitors or supercapacitors are designed to handle sudden energy demands over a short period of time. Short term energy storage is needed for operations such as frequency regulation, voltage control and spinning reserves to name but a few.

Benefits of hybridisation can be experienced with a combinational of technologies with the benefit of extending the lifetime and improving the efficiency of the primary storage solution and in the long term potentially positively impacting on the overall cost of investment. Herein the expectation is that in tandem, the solution performs optimally but also with the added advantage of extending the lifetime and SoH of the primary storage scheme. Extending the lifetime of energy storage assets in the future renewable energy grids will result in huge economical advantage while making sure resource efficiency is also maximised, impacting sustainability positively. Furthermore, combination of high-power packs and high energy packs can mean that intensive power burst operational modes can be handled by the high-power packs (peak shaving etc) while the large energy demand being met by the high-energy density storage schemes. Such an operational segmentation can also result in reduced degradation and extension of lifetime of the overall storage system.

Potential hybridisation solutions examples:

- Redox flow battery in combination with Li-ion based BESS, hybrid of high-power storage and high-energy storage hybrids.
- Niche applications which apply pumped hydro with flow battery to increase life-time.

Research needs:

- Increase lifetime, the cycle life and the resilience of battery systems thus extending the life of the system.
- Significant decrease of cost of batteries specifically for hybrid stationary energy storage
- Investigation of lifetime thresholds and triggers for aging/degradation for the HESS and develop predication models for the individual components.
- Decrease the cost of the Energy management system for the HESS.
- Control systems with new DC architecture to determine the most efficient way to prioritise the use of the hybridised energy storage solution.
- Development of efficiency operations – with the support of digital twins, real time models of the HESS is necessary.
- Forecasting energy demand and supply using machine learning and artificial Intelligence.

5.2 Large scale and micro-grid assisted UPS solutions for critical infrastructure

Today's uninterrupted power supply (UPS) solutions are primarily designed to protect the control units of large centres, infrastructure or industrial processes such as data centres, telecommunications infrastructure and hospitals.

For larger UPS solutions, such as those used in hospitals, data centres and military facilities today diesel generator sets are used to protect these critical infrastructures. These generators are coupled with a switch that is activated when the main power supply is interrupted. The use of diesel generators, add to greenhouse gas emissions and they require regular maintenance. For smaller infrastructure, the energy storage of these solutions, range from 1 to 3 hours in duration, allowing for a controlled shutdown of processes during a power shortage. The main battery type used in these UPS systems are gel-type lead acid batteries, which have a long lifespan if kept under float charge. In the case of telecommunication stations, solutions typically utilise more expensive, 30 minutes duration, LIBs as backup power. In critical telecommunication infrastructure, such as radio communication for police or fire brigades, larger lead-acid based battery storages can be utilised.

While hybridisation of UPS solutions on small scale are not necessary, it may serve to improve the system on the larger scale if the costs of the HESS is lower than the cost of a single energy storage system.

In times of political uncertainty, it becomes important to secure not only critical infrastructure but also less critical but fundamental infrastructure on a broader scale. The emergence of renewable energy sources and stationary energy storage has made the supply and protection of infrastructure even more crucial. In this context, DC-connected grids with renewables and stationary storage can play a vital role. To operate such a DC-intersected grid, both short and long duration storage systems need to be integrated to meet power demands, including covering power spikes and providing energy for extended periods of operation. Possible BESS solutions could be RFB or high-temperature sodium batteries in combination with supercapacitors or high-power LIB. When combined with renewables, these secured micro-grids can offer a resilient grid scenario where a portion of the installed battery power is used to operate the infrastructure. This ensures prolonged independent operation without the need for refuelling, leading to a resilient and environmentally friendly infrastructure.

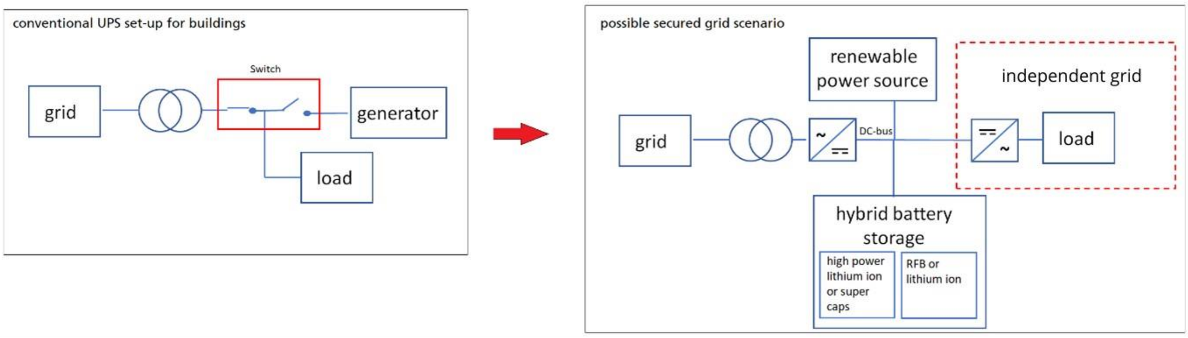

Figure 1: Schematic representation of conventional layout of UPS applications (left) and the concept of secured mini- or micro grids (right)

The business case for such UPS systems beyond small scale usage is unclear, due to market design factors, including the question of who is responsible for the maintenance and ownership of the service which is a “back up”. It is expected that this may require legislative steps to enforce such systems.

Research needs:

- Optimal configuration of HESS relative to the needs of the UPS system.
- Increase reliability and flexibility of energy supply relative to the needs of the UPS system.
- Develop hardware components on multi megawatt scale specifically for HESS. This is currently available for wind turbines but is not considered for use with HESS up to MW level.
- Develop load management tools to maintain the baseload supply of critical infrastructure 24/7. This is also based on the system design of UPS “microgrid”.

5.3 Hybrid energy storage solutions for energy islands

Energy storage technologies, coupled with advanced power electronics systems, are key to maintaining electrical system reliability when faced with increasing installation of renewable energy resources. Island grids are per definition, weak electrical systems, where stability issues are crucial in the pathway to integrate renewables. Two main challenges have to be addressed in the coming years:

1. **Short term renewable instability** – Fluctuation of renewable generation create grid frequency and voltage fluctuations that are amplified in a weak grid as islands have, so technologies to provide fast primary regulation (range of ms) are fundamental to go ahead with a decarbonised energy system in islands.
2. **Long duration storage** – Due to the resource availability (wind and solar), in order systems to move big amounts of energy from days to weeks, are necessary to integrate a percentage of renewable energy higher than 60-70% (approx. numbers to be assessed case by case).

Hybrid storage system has the capability to solve both two main issues to integrate a large amount of renewable energy in European islands. As example, a flow battery hybridised with a LIB unit can provide both services in an optimised system, or a hydro pump plant coupled with a LIB to provide fast primary regulation to the island. In the meantime, while conventional generation is needed to support renewables integration, hybridisation schemes like a LIB unit coupled to a gas unit can join fast primary regulation capabilities of a battery, with long term demand support of a gas unit, reducing the need to operate the system with a big conventional power reserve, and generation unit dispatched at low eff point of operation.

Research needs:

- Development of advanced control systems to integrate different assets for fast primary regulation.
- Optimal design configurations to provide frequency primary regulation and long storage capabilities with high operational efficiency.
- Simulation environment and digital twin developments to improve islands renewable scenarios assessment (hybrid storage but also renewable generation simulation tools).
- Long duration storage with an incremental energy density to reduce land occupation (critical island issue).

5.4 Momentary reserve with RES

The energy market covers time-ranges from milliseconds to maximum a few days ahead in advance. Currently, there are no markets for the provision of power and energy for ultrashort or ultralong durations. In the past, there was no need for markets in these time domains as power control was achieved through spinning masses in power plants for short durations and a secure supply of fossil energy sources for longer durations. However, with the phasing out of fossil fuel-driven power plants, the growing demand for solutions, and the increasing intermittency of generation (from solar or wind parks), there is a need for solutions to address the resulting supply insecurity.

The absence of spinning masses, which play a crucial role in stabilising the grid in ultrashort durations, will impact power quality. Power quality is determined by synchronous sine waves of alternating current and balanced power in each of the three phases. The switching time of regular power electronics used in grid inverters operated by renewables or storage is typically too slow to meet the demand for ultra-fast power control. Therefore, the transition from regular power plants to power electronics-operated renewable energy sources will create a greater demand for fast power control. This demand will initially arise in larger islands or more isolated grids with a high penetration of renewables but could also become significant on the mainland as conventional solutions for baseload generation are phasing out.

Several solutions can meet this demand. For instance, researchers are exploring the utilisation of the inertia of wind turbines to generate virtual inertia in the grid. Another viable solution for ultrashort durations is the development of power electronics with fast-control capabilities, enabling power compensation within half a wave of a sine water (in the kHz range). This could enable renewable energy providers to function as fully-fledged power plants. However, to ensure the necessary power and continuous energy supply, a hybrid energy storage solution comprising both short and long duration storage is the most viable option, akin to a conventional power plant. The short-term storage component could potentially be supplied by ultrafast supercapacitors (referred to sometimes as ultracapacitors), but these must be part of a hybrid energy storage system.

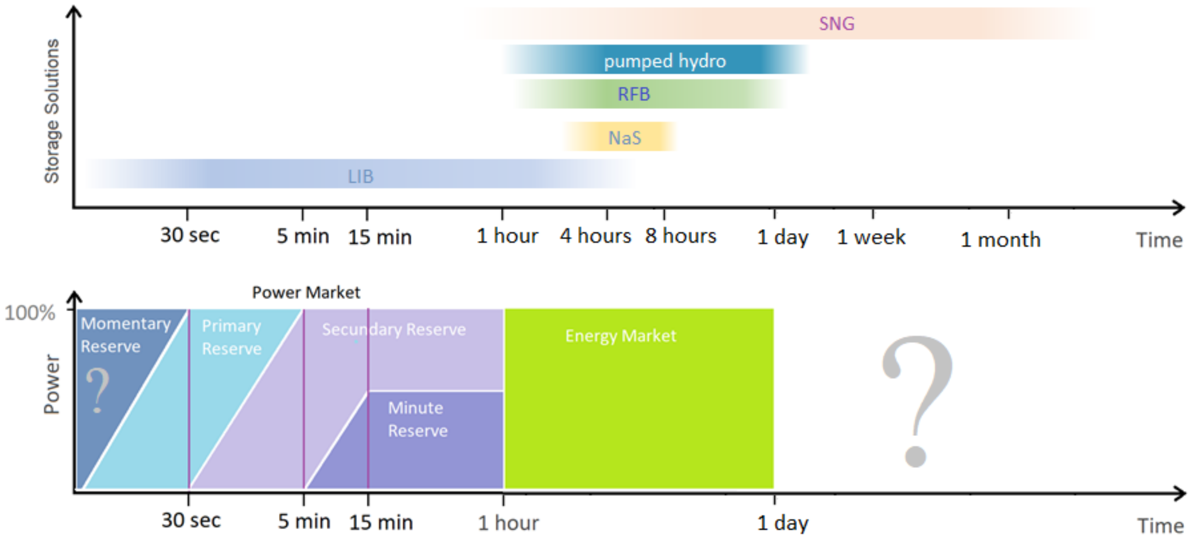

Figure 2: Scheme of a typical time dependant energy market in Europe (could differ from country to country) as well as potential energy storage options (LIB = lithium-ion batteries, NAS = high temperature sulphur batteries, RFB = redox flow batteries, SNG = synt)

Business case: Currently the market design is unclear, however with increasing installation of renewable energy and the decreased use of fossil fuel energy, power quality will need to be addressed for larger islands in Europe which are not well connected to the central grid.

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

Research needs:

- Development of fast- control of inverters in the range of several 10 - 100 kHz
- Scaling up the HESS with inverters to ensure quality of power.
- Combination of long- and short-term energy storage on multi-MW solutions to allow renewables to act like a power plant on the energy market.
- New business models for momentary reserve, grid-shaping, improvement of power quality.

5.5 Hybrid energy storage solutions for deferral of grid investments

Electricity grids in many parts of Europe (including the Netherlands) are reaching their capacity limits[5]. This is caused due to a mismatch between the demand and supply, especially in the High Voltage network. Expansion of power grids is both expensive and time-consuming and needs critical planning and hence solutions of energy storage that can augment or reinforce grid capacity is essential, especially in those cases where access to the High Voltage/Medium Voltage network is difficult or simply not possible. Thus, virtual power grids or microgrids with energy storage which can relieve the need for an augmented centralised power grid is needed. Hybridised energy storage schemes with provision for ancillary services while also meeting the local energy needs for the capacity augmentation can be key applications that such a virtual power plant can serve. Furthermore, accurate tracking of SoH of the hybrid storage scheme (as described above in section 4.2 -Hardware for Communication and Sensing for Energy Management System) can yield an extension of useful lifetime of the overall storage system, thereby saving huge capital investments in billions both at the power system capacity augmentation level but also in the hybrid BESS maintenance costs. HESS can thus be used as a mean to defer upgrading very costly and difficult to access infrastructure such as cables and converters while enabling ancillary services operations.

Research needs:

- Develop lower cost, reliable batteries with low or no dependence on critical raw materials.
- Prototype to demonstrate the hybridising of the energy storage system.
- Sizing and Demonstration of the feasibility of the proposed technology.
- Analysis of best placement of hybrid system in the energy system, identify critical points for potential installation.
- Consider use of 2nd life batteries in this a hybridised energy storage system.
- Linking projects which create hybrid energy storage demonstration to achieve best learning outcomes.

5.6 Grid booster – CAPEX deferral phase

The installation of high-voltage transmission lines is a significant investment. To postpone the large-scale investment in costly transmission lines, battery storage installations could be employed. One widely discussed scenario is known as the "grid booster".

Typically, transmission lines operate below their full capacity to allow for the dissipation of energy over alternative lines during emergencies. In a grid booster concept, the safety margin of transmission is utilised to transfer more energy over the existing power lines, and instead utilise battery storage to be the safety margin in the transmission line. Therefore, the batteries in a grid booster offer an alternative safety mechanism. Large-scale battery installations are placed at central connection points along the transmission line to absorb excess energy during emergencies, while transmission lines operate at their maximum capacity. This concept can in principle also be added up with other services for the grid operator.

Tesla.Inc has built a 100MW project in Adelaide, Australia, and recently an installation of a 250MW grid booster in Kupferzell, Germany has started by Netze BW. Additionally, Fluence Energy Inc. and Tennet have announced a 100MW/100MWh project in Ottenhoven and Audorf Süd, Germany. It is worth noting that none of these projects currently incorporate HESSs. For example, the Kupferzell plant exclusively employs LFP batteries. However, the implementation of HESS could yield significant benefits for such applications. Combining long-duration Redox Flow Batteries with high-power LIBs combinations could provide both rapid response capabilities and high capacities, enabling longer utilisation of the grid-booster mechanism. Hybridisation can facilitate the storage of energy for a long duration (up to months) of time, LIBs are not highly efficient in this regard so the use of hybridisation in this case would be beneficial with regards the anticipated losses of energy and hence cost.

Research needs:

- Extend grid models to incorporate hybrid energy storage grid boosters to defer building of massive grid infrastructure with HVDC links.
- Demonstrate flow batteries along with Li ion batteries in a grid booster and study of costs.
- Develop a digital twin of the grid with HESS included.
- Develop business cases and policy both nationally and cross European boarders.

5.7 Single-family homes (<50kWh/day) - Utilising batteries and heat storage options to achieve better efficiencies of battery systems

Usually long-duration storage systems have a lower efficiency than short-duration solutions. This means, that in these kinds of systems depending on the generation costs and lifetime, the OPEX costs can exceed the CAPEX costs[6]. If the application has also a heat demand like residential solutions, there can be an incentive to increase efficiency by hybridising the BESS with a heat storage solution. This is especially the case in residential energy storage solutions. In the past, a few of such HESS solutions have been built (see e.g., project BiFlow) to utilise the high heat capacity of a RFB storage in combination with a heating element and an additional heat storage to utilise waste heat of the RFB. Such combinations can also be extended to larger scale to allow district heating, e.g., with a community storage which distributes preheated water with low insulation demand to individual heat-pump and heat storage units. These concepts could bring new efficient solutions to the residential market.

Research needs:

- New hybrid battery solutions with integrated battery storage for residential applications, maybe in addition with heat pumps or geothermal storage or classical heat storage for increased energy efficiency. A special application could be e.g., long duration community storage with near-distribution heat grids and local heat pumps.

5.8 Vehicle to Home (V2H) and Vehicle to Grid (V2G)

This area of V2H and V2G is not strictly under the topic on hybridisation, however the experts of the Task Force Hybridisation feel it is important to raise awareness of this topic and use this opportunity to highlight its huge potential benefits to society as a whole.

Concerning V2G, it's easy to imagine thousands and tomorrow millions of vehicles feeding energy back into the grid during peak consumption hours (when workers return home in the evening), thereby limiting peak consumption. V2G is foreseen to be operated at low power because the impact on the battery aging is lower and the battery efficiency is better. With the aggregation of thousands of EV in a town or region can easily result in reaching high reinjection power. Charging of vehicles can then take place during the night when usage is generally low.

Despite the absence of technological barriers on bi-directional chargers in vehicles, V2H and V2G solutions are still very marginal in the world of electric vehicles. However, they could bring value to both vehicle owners and electricity grid operators.

Concerning V2H, being able to use the energy from its own vehicle at home, would make it possible to:

- replace the grid for short periods when the grid disappears.
    - use during the day cheaper energy charged at off-peak times during the night.

- and potentially reduce the maximum power of its electricity contract, and therefore its cost.

The roll out of the V2H and/or V2G technology in Europe is hampered currently mostly due to policy. In addition, there is a lack of clarity concerning who has the responsibility for electrical management as this is bidirectional and requires bidirectional power electronics. It also requires a good deal of trust to enable this. There is a need for both policy and legislation change to create a flexible business model for V2H and/or V2G applications.

Research needs:

- Advancement and demonstration of bidirectional batteries in vehicles for use in V2H and V2G, not only at vehicle level but also at a fleet of vehicles level, to have significant impact on the grid.
- Improve the efficiency of bi-directional chargers especially at low power (around 2-3kW) .
- Technology, including new sensors to enable practical real time testing of State of Health (SoH) of battery.
- Analysis of the impact on SoH of battery systems over extended cycling

To see these solutions adapted on a large scale, it will be necessary to measure more precisely the impact of these additional charging/discharging cycles on battery ageing, and then evaluate and subsequently reward the contribution of the end-user to the grid.

5.9 Neighbourhood batteries / high power with high energy

Batteries when installed in a house result in unused capacity, with a battery cycling within a smaller thresholds of SoC. This results in a reduced capacity utilisation factor of the energy storage system and hence is an inefficient use of the resource. A more centralised approach within a neighbourhood or sub-regional level can mean better utilisation of the battery, also now considering battery playing a role in grid congestion and ancillary service provisioning apart from storage subscription to the individual houses. Further, a shift of storage scheme from the individual customer level to the sub-regional level would mean reduced costs for the customer while ensuring higher added value o the services offered.

A HESS (e.g.: LiB + Flow Batteries) can yield a total cost of ownership (TCO) reduction while enabling an interconnected and reconfigurable network of energy storage to aid the grid for both proper operability but also during contingencies. Furthermore, apart from a stationary neighbourhood battery, several mobile batteries of parked EVs can form an interconnected storage pool that can serve as a neighbourhood battery when upgraded with V2G possibilities. In such case, the mobile batteries present a case where, advanced BMS in combination with diagnostic and health assessments to manage energy, SoH and Remaining Useful Life (RUL) of the connected individual batteries becomes important.

Business case: Policy and ownership of battery is the main issue here. In addition, a good business case for both stationary batteries and mobile neighbourhood EVs-V2G needs to be developed.

Potential hybridisation solutions:

- RFB + Li-ion Batteries (High Power/High Energy) (Stationary Neighbourhood Batteries)
- Li-ion Batteries of varied chemistries for mobile neighbourhood batteries

Research needs:

- Advanced BMS and diagnostics for stationary and mobile battery-based neighbourhood batteries.
- V2G infrastructure and interconnected mobile EV batteries as stationary batteries – (neighbourhood EVs-V2G).
- Energy management and ancillary services provisioning in both stationary and mobile neighbourhood batteries.
- For EVs in the neighbourhood, several different EVs (brands, OEMs, capacity, chemistries etc.) with different battery packs, SOH, RUL, BMS etc. will all need to be integrated.
- Peak shaving with high power storage technology and energy storage with high energy storage for preventing over sizing and high-capacity utilisation.

6 CASE STUDIES FOR HYBRIDISATION OF ENERGY STORAGE IN TRANSPORT

6.1 Waterborne

In Europe the maritime transport sector has been taking action and is continuously researching and implementing new technology to transition to zero-emission. One of the main leading bodies in this sector transition is the Waterborne partnership7 which identifies and, together with the European Commission and industry, funds much of the necessary research to achieve zero emission waterborne transport. This very transition is in turn complicated by the many policies, rules and regulations that govern the maritime shipping sector on several levels. Achieving zero-emission waterborne transport concerns approximately 55,000 merchant ships and around 12,000 inland vessels and has two aspects:8 while part of the existing operational fleet must undergo retrofitting, the remaining vessels will be replaced by new-builds. The latter will be required to become zero emission as soon as possible, by for example employing electric and/or battery drives and adapting their onboard fuel storage in a way that would ease the transition to hybrid power units.

One way to test and prove innovative technologies for maritime greening is retrofitting existing vessels which operate with relatively small power demands by for example, converting their propulsion systems to battery electric or fuel cells, as well as employing containerised energy storage for batteries. The need for retrofitting is quite critical considering the low turnover of the fleet and the large number of old operational vessels with low energy efficiency and large environmental impact, such as for inland waterway vessels. Another obvious target for retrofitting is cruise ships, which require high amounts of energy. Since they operate on an electric drive system, they will require electric energy storage and energy harvesting technology. For new-build cruise ships, hybrid energy systems such as fuel cells in combination with batteries and combustion engines are envisioned in addition to the above-mentioned energy harvesting and storage options.

Ferries are ideal candidates to become fully electric or employ fuel cells. However, for both new build and retrofitted ferries with a range of up to 200 nautical miles, the focus will also be on hybrid systems (a combination of ICE/electric drive, fuel cells, battery packs and renewable energy) allowing for full battery electric transit and zero emissions during approach and harbour stay. For ferries with ranges above 200 nautical miles, the most applicable solution remains ICE combined with alternative fuels.

For offshore vessels, which come in a large variety of sizes, the most applicable designs include full-electric and hydrogen-powered fuel cell solutions. Currently however, some of the new-build offshore vessels already operate on hybrid battery systems. One example is a hybrid design comprising hydrogen-powered PEM fuel cells combined with diesel ICE (p. 23 in SRIA report)[9].

From the point of view of the environmental impact on climate change stemming from the maritime sector, the main challenges are air pollution, water pollution and noise pollution (in particular underwater noise). Both the use of sustainable fuels and hybridisation (where electricity will be used as an auxiliary power source) contribute to attaining these three environmental objectives. In new builds, this means that the vessels will have an electrical drive which would allow a hybrid power design that includes batteries, fuel cells and ICE. The research priority medium-term is the development of ship systems capable of reaching overall efficiency of minimum 60% range by use of fuel cells alone or with hybrid systems.

One important operational objective within the hybridisation of the maritime shipping industry is related to port-based activity/port infrastructure[10] which is addressed in Section 6 below.

Research needs:

- Standardisation of the installation within a wide range of ships and of the integration within electrical grids (AC and DC).
- Standardisation of the charging connections between the vessel and the shore, both in ports and charging hubs.
- Improving the operational benefits of batteries while ensuring longer zero emission sailing.
- Upskill shipowners and operators in best decision making and operation.
- Optimal ESS sizing and hybridisation based on real operational load profiles and need for open-access data.
- Modular multi-MW heterogeneous battery systems, intelligent power electronics (with condition monitoring) for optimal operation.

6.2 Aviation – Hybridisation for light duty & heavy duty aircraft

Aviation is accountable for less than 5% of the global CO2 emissions[11]. Even though this may seem like a relatively low figure, the climate impact from aviation is significant in light of everything that we must decarbonise in order to reach net zero emissions by 2050. Decarbonising aviation is not an easy task; electric-hybridisation and electrification of aircrafts come with increased onboard weight, which in turn leads to the aircraft needing even more power to perform; this is the so-called ‘snowball’ effect[12], a term often used in the aviation context. That being said, it was already shown that implementing hybrid-electric aircraft technologies and phasing out fossil fuels in short-range aviation may lead to significant benefits to both human health and ecosystems’ quality. As such, one of the key aspects towards zero and low emission technologies within aviation is research into novel hybrid-electric solutions (distributed/electric propulsion) and their incorporation into regional and short-range flights as was also highlighted in the 2021 SRIA from the Clean Aviation Partnership[13]. This will trigger the development of new and efficient designs for aircraft configuration, in particular when it comes to flight control and on-board energy concepts. Electric propulsion is a promising concept for optimised aircraft performance and reduced fuel consumption. The developments in the hybrid-electric technology will further be of use for commuter and vertical lift applications. Hybrid electric and dual-fuel concepts are considered, as well as concepts with hydrogen fuel-based propulsion coupled with advanced battery technology energy storage.

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

The first candidates in the aviation sector that will adopt hybrid-electric propulsion technology are aircrafts operating at distances of less than 500 km (regional connections) with a capacity of less than 100 seats. It is expected to have this concept ready for commercial application by 2035. Different hybrid systems are being tested, such as either a thermal engine coupled with electric configuration, or a fuel cell system coupled with electric configuration.

Several hybrid architectures are under investigation including hybrid-electric (parallel hybrid and series hybrid) and turbo-electric. In the hybrid-electric design, when the additional electric energy is not used for high power demand actions such as acceleration, it can be stored in batteries.

In the parallel hybrid-electric structure, the thrust is generated by a conventional thermal engine coupled with an electric engine in high power demand flight phases such as take-off.

In the series hybrid design, electric power is provided by a generator plugged into the main turbo engine and either stored in a battery when not in use or used to power electric motors and propellers.

In the turbo-electric design, the electricity generated by a turbo machine via a turbo shaft is used to drive multiple, distributed fans, driven by electric motors.

For larger regional aircraft it is envisaged to develop a system based on a hybrid turbo-propeller equipped with a reversible thermal engine and coupled with batteries or fuel cells for additional propulsion power during critical phases in flight.

All power during taxi and gate related activities will also come from batteries and fuel cells.

One of the main research challenges it to develop a power management system to ensure an optimum split of the power source according to the flight phase. The total on-board power for regional flights will range from 2 to 8 MW, depending on the size and degree of hybridisation. The electric configuration may include efficient hybrid turbo propellers, electrical foldable propellers, electrical power storage, and all the necessary systems needed to implement a power channel above 1MW/1kV.

With regards to larger aircraft which travel over longer distances, micro-hybridisation may be a method to reduce emissions and fuel consumption. This is where smaller batteries systems are used to assist the thermal propulsion engine with some of the system tasks on board. According to Airbus, micro-hybridisation could increase fuel efficiency and reduce the environmental impact from the aircraft industry by 1-6%, and even 10% in the case of helicopters.

Research needs for the electrification/hybridisation of the aviation sector.

Specifically with relation to batteries:

- Development and manufacturing technology for light weight batteries systems and components to support Hybrid energy storage systems (HESS) in aviation.
- Developing the integration and adaptation technology of a modular hybrid power pack (energy cells, power cells, high charge/discharge cycle); designing batteries for peak power delivery, along with the possibility to enable a high discharge current.
- Developing batteries and/or fuel cells with the ability to deliver high power in a relatively short period of time.
- Developing batteries capable of withstanding sudden temperature and pressure fluctuations.
- Developing technology for in-flight battery swapping.

For aviation in general:

- Developing an efficient hybrid configuration to provide both electrical and mechanical power for propulsion for example a turbo-generator (thermal engine + electric generator(s)) or a hybrid turbo-propeller
- Achieving modularity and developing a hybrid system to adapt to changing propulsion power ranges and to interface with aircraft electrical systems.

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069676

7 CASE STUDIES FOR HYBRID ENERGY STORAGE RELATED TO CHARGING INFRASTRUCTURE

7.1 Hybrid refuelling-recharging infrastructure and hubs

While the case of refuelling-recharging of hybrid energy storage systems may not be strictly classed as hybridisation in itself, it is an important factor to enable the success of hybridised energy storage systems in transport. Fast charging has been a topic of discussion and research for some time and it continues to be an essential issue for aviation and waterborne transport among others. However, when we consider hybrid energy storage systems several additional group questions arise, among them the most challenging topic of how to refuel-recharge multiple systems in parallel in a safe manner.

For all transport modes, but in particular aviation and shipping, one very important aspect of integrating HESS is redesigning the seaports and airports in such a way that different fuel types and new technologies are accommodated for concomitant storage, as well as refuelling/charging. Special attention needs to be granted towards the safety of all ground activities, but in particular where the area is limited and activity levels are high. Large initial investments will need to be made for supplying power generation and other fuels such as hydrogen liquefaction and storage. The new infrastructure for the shift to alternative propulsion will thus need to include upgraded grid connections and fuelling possibilities regardless of the fuel type (SAF or liquid hydrogen), in additional to the provision of local power distribution infrastructure.

Safe storage and handling of liquid hydrogen (which must be kept at temperatures below 240°C) will be challenging for both seaports and airports. Furthermore, consideration needs to be taken for safe onsite generation and storage of electricity in relative proximity to onsite storage and handling of flammable fuels.

In the case of maritime transport, an important addition to the current port infrastructure is the construction of the offshore recharging/refuelling hubs. This would allow hybrid ships to recharge and/or refill outside the main port thus reducing congestion and waiting times. One of the challengers here could be supplying sufficient energy to the energy hub offshore. The same considerations on storing electricity and flammable fuels close to each other are valid here.

Research needs:

- Development of fast charging batteries and infrastructure essential to maritime and aviation
- Modelling of multiple refuelling - recharging systems in parallel with considerations for safe design of the system.
- Development and small-scale demonstration of physical infrastructure for multiple refuelling - recharging systems.
- Development of digital twins for safe refuelling – recharging in real time.
- Building a sound economic and financial business case for dual refuelling - recharging infrastructure and accessing who could operate and take on responsibility for the same.

7.2 Charging Infrastructure – The Electric Road

The electric road allows a vehicle to charge and drive at the same time over a short duration. It involves part of the road being providing wireless charging to the vehicle as it drives over it. This solution is very interesting especially for trucks which need a large amount of energy for their trips, involving large, heavy batteries and costly fast charge infrastructures. On section of roads without charging infrastructures (Electric Road), the vehicle will use its own battery. The first studies show than it could be possible, with this kind of solution, to divide by three the size of the integrated batteries. Of course, a lot of technical challenges need to be addressed: safety, electric contact, DC grid deployment, etc. The potential benefit of the electric road is that this static and dynamic charging infrastructure resulting in the battery in the truck being smaller (thus lighter weight).

Research needs:

- Optimisation of battery technologies enables higher C-rate without impacting on aging.

Potential hybridisation solutions add the research questions posed:

- What is the optimum, size, technology of the battery depending on electric road charging capabilities?
- How to manage, in real time, the energy coming from the road (DC grid) and from the battery, depending on the state of charge, charging grid capabilities, etc.

8 POLICY IMPLICATIONS

In the past years, under the Green Deal[14], the European policy framework for storage has seen significant improvements. Indeed, the revised Electricity Market Design[15] and the Fit-for-55 Package[16] acknowledge the role of storage in the future decarbonised system and, if correctly implemented, they will fuel the demand for storage solutions while consolidating their business case and facilitating their roll-out. Examples of how these new legislative texts can directly or indirectly enable use cases for hybrid storage systems include:

- Electricity Regulation[17] for stationary storage (with provisions on national flexibility assessments, national flexibility targets, and the possibility for Member States to implement capacity payments for new non-fossil flexibility assets)
- Energy Efficiency Directive[18] for storage solutions in buildings
- Alternative Fuels Infrastructure Regulation[19] for recharging solutions, vehicle-to-home solutions, and vehicle-to-grid solutions (the text focuses mainly on cars, vans, and trucks, but it also promotes electricity supply at ports for ships and inland waterway vessels and electricity supply for stationary aircrafts)
- RefuelEU Regulation[20] for aviation and the FuelEU Regulation[21] for maritime transport.

Despite this supportive framework, important obstacles still need to be addressed to unlock the potential of hybridisation.

1. There is no legal definition of a hybrid energy storage system

In line with the principle of technological neutrality upheld by the European Union, the new policy framework is mainly application-driven, it promotes mobile and stationary storage systems without clear-cut signals in favour of certain technological choices. While this approach is justified to enable fair competition in the market, in particular to the benefit of innovative solutions, this means that hybridisation has yet to be recognised as a concept.

It should be noted that the legal definition of energy storage in European law[1] reflects this principle of technology neutrality and hence does not exclude hybridisation. Nonetheless, to make sure that hybrid storage systems can also benefit from the new policy framework mentioned above, a joint definition of hybrid storage systems accompanied by further guidance from the Commission would be welcome. It could for instance help Member States in their transposition of the new provisions of the Renewable Energy Directive regarding permitting for storage facilities.

---

[1] Article 2 (59) of the Electricity Directive: "'energy storage' means, in the electricity system, deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier;"

This project has received funding from the European Union's Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

2. The regulatory framework remains very fragmented

The policy framework remains greatly fragmented, with Member States fostering different approaches. And, as the implementation of the revised Electricity Market Design and the Fit-for-55 Package leave a lot in the hands of the Member States, this fragmentation is unlikely to diminish.

Three areas should especially be addressed:

- **Ownership of stationary storage** assets is governed by the Electricity Regulation. Transmission and distribution system operators should not, in principle, own and operate storage facilities, but are granted a number of exemptions (which differ from one Member State to the other). This makes it especially difficult to develop business models for hybrid storage systems based on diversified activities.

- There is **little legal certainty** for new ownership models such as storage owned by local energy communities. Efforts to improve legibility for project promoters would be welcome.

- **Safety** (including fire safety) requirements are critical for hybridisation. Indeed, hybrid storage systems face specific challenges linked to technology (e.g. combining batteries and hydrogen storage) and to application (e.g. more stringent rules for waterborne transport). Simplification and standardisation of safety requirements will be instrumental for the successful roll-out of hybrid systems. In the short term, in view of supporting innovation, knowledge-building should be promoted.

3. The business case for energy storage solutions should be further consolidated

The European Union has acknowledged the role of storage in increasing the penetration of renewables, containing electricity prices, and maintaining security of supply. However, building compelling business models for storage projects remains quite challenging. Even more so for hybrid systems and long-duration energy storage systems. This is because storage assets must rely on revenues stacking i.e. combine revenues streams from different markets (wholesale markets, balancing markets and ancillary services markets, capacity markets). Further attention should be granted to this issue.

Besides the three obstacles highlighted above, it could be useful to address other open questions like:

- **Certification of "green" electricity** when stored in a hybrid system (here, the Delegated Act on the definition of renewable hydrogen[22] could be used as a benchmark as it covers storage in its criteria on temporal matching).
- **Standardisation** for vehicle-to-grid and vehicle-to-home solutions - here, the Alternative Fuels Infrastructure Regulation[23] provides for the development of technical specifications, notably on communication between vehicle and recharging point for the purpose of interactions with the electricity grid. Finally, policy-driven opportunities for hybridisation should also be explored, notably:
- **Production of e-fuels for the aviation and maritime** sectors, as well as hydrogen production for the decarbonisation of hard-to-abate industries, as it will rely on a steady supply of renewable electricity to run electrolysers.

- **Security and resilience of critical infrastructure** - hybrid storage systems could help secure the energy supply for critical assets in the event of natural disasters, health emergencies, or man-made threats.

Generally, deployment of hybrid storage solutions to phase-out fossil fuels and help reduce the cost of energy, in line with the ambition set out in the REPowerEU Plan[2].

9 RECOMMENDATIONS AND CONCLUSIONS

The ongoing aim of the European Battery research community is to create lower cost, reliable, safe and sustainable batteries, however in order to gain the advantage of implementing these batteries in combination with other technologies corresponding actions are needed. In order to achieve the widespread, large-scale distribution of HESS the following actions are required:

- **Develop diagnostic techniques for SoH, both hardware and software (see also the position paper of the Task Force Digitalisation) and specifically for HESS, develop methodologies to combine these SoH diagnostics for hybrid systems.**

- **Develop efficiently power electronics for control of HESS which will integrate within electrical grids, in both AC and/or DC.**

- **Development of business cases for HESS is key to avoid experiencing greater strain on grid due to increase on usage and increased renewables. In islands grid systems this will be more pronounced, and it will be the first place where we experience these issues.**

- **Support the development of a lasting network of researchers, industry, member states and EU commission which will collect and correlate data from past and existing projects to ensure sharing of the lessons learned. This community could also serve to provide guidelines for decisions of industry and policy makers developing the European energy and transport systems.**

In addition to research, policy and legislation will be needed to drive **business cases** for the implementation of HESS in order to drive the future energy transition. This policy needs careful consideration which must be based on a sound scientific background which can be supported by the research community.

10 REFERENCES

1 European Commission. REPowerEU Plan. (2022). EUR-Lex - 52022DC0230 - EN - EUR-Lex (europa.eu).

2 European Commission. Commission Recommendation of 14 March 2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system 2023/C 103/01. EUR-Lex - 32023H0320(01) - EN - EUR-Lex (europa.eu).

3 Santos B. China connects world's largest redox flow battery system to grid. (2022). China connects world's largest redox flow battery system to grid – pv magazine International (pv-magazine.com)

4 Battery2030+ - Battery 2030+

5 https://www.tennet.eu/markets/dutch-market/studies-congestion-management

6 Example: 65% efficiency, with generation costs of 0.1€/kWh over a projected lifetime of 20 years with one daily cycle => inefficiency costs = 0,35*0,15€/kWh*365*25 ≈ 480€/kWh in comparison of e.g. typical CAPEX costs of 350€/kWh

7 Partnership - waterborne.eu

8 Waterborne. Strategic Research and Innovation Agenda for the Partnership on Zero-emission Waterborne Transport. (2023). 230505_SRIA_Zero_Emission_Waterborne_Transport_2.0_clean_public_consultation_final.pdf

9 Ibid.

10 Rogerson S., Costa N., Ekholm J., et al. SeaCharging Investigating the Need for Standardised Charging Infrastructure for Maritime Electrified Vessels. (RISE Research Institutes of Sweden, 2022). https://www.diva-portal.org/smash/get/diva2:1738869/FULLTEXT01.pdf.

11 Bergero, C., Gosnell, G., Gielen, D. et al. Pathways to net-zero emissions from aviation. Nat Sustain 6, 404–414 (2023).

12 Roboam, X. A Review of Powertrain Electrification for Greener Aircraft. Energies 2023, 16, 6831. https://doi.org/10.3390/en16196831.

13 Clean Aviation Joint Undertaking. Strategic Research and Innovation Agenda 2021. CAJU-GB-2021-12-16-SRIA_en.pdf (clean-aviation.eu). CAJU-GB-2021-12-16-SRIA_en.pdf (clean-aviation.eu)

14 European Commission. Communication on The European Green Deal. (2019). Communication on the European Green Deal.

15 European Commission. Commission proposes reform of the EU electricity market design to boost renewables, better protect consumers and enhance industrial competitiveness. (Strasbourg, 2023). Proposal for a revision of Electricity Market Design.

16 More details on the Fit-for-55 Package on the European Commission website here.

17 European Commission. Electricity Market Design revision. (2023). Electricity Market Reform for consumers and annex - European Commission (europa.eu).

[18] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). Energy Efficiency Directive.

[19] Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU. Alternative Fuels Infrastructure Regulation.

[20] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). RefuelEU Aviation Regulation.

[21] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. FuelEU Maritime Regulation.

22 Delegated regulation - 2023/1184 - EN - EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.157.01.0011.01.ENG&toc=OJ%3AL%3A2023%3A157%3ATOC.

23 Regulation - 2023/1804 - EN - EUR-LEX. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1804&qid=1699372860283.

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

ANNEX A - LIST OF SELECTED PROJECTS

Overview of selected currently running hybridisation projects

Application Area	**Project**	**Combined technologies**	**Expected end year**
Waterborne	SEABAT Horizon xxxx call xx project	Combined battery technologies	2024
Automotive	HELIOS (H2020) High-pErformance moduLar battery packs for sustaInable urban electrOmobility Services	Two battery types (NMC+LTO)	2024
Stationary	HYBRIS (H2020)	Two battery types (AORFB+LTO)	2024
Stationary	SMHYLES (Horizion EU - Just started) Safe, sustainable and Modular HYbrid systems for Long-duration Energy storage and grid Services	Aqueous-based HESS (Vanadium RFB + Aqueous supercapacitor), Salt-based HESS (NaNiCl2 battery + Aqueous supercapacitor) and HESS (Supercapacitor + Vanadium RFB with storage extension)	2028
Stationary	ISTORMY (H2020-LC-BAT-9-2020 n°963527)	Interoperable, modular and Smart hybrid energy STORage systeM for stationarY applications	2023
Stationary + EV charging stations	HAVEN (Horizon EU - Just started) High-PerformAnce Hybrid Energy Storage System for multi-serVicE provisioNing		?2027-8?
Stationary	HYFLOW (H2020)	Vanadium RFB + Supercapacitor	2024
EV charging stations	HEROES (H2020)	Li-ion battery + Li-ion capacitor	2024
Stationary + EV charging stations	OMEI (German federal funds) Coordinator TZE	2nd life Li-ion battery + Organic RFB for charging infrastructure	2023
Stationary storage	BYFLOW (German federal funds)	Vanadium flow batteries & Heat storage & Li ion batteries for residential applications	2024
Automotive Sector	R&D Project Uncovers Innovative Win-Win Combinations of Lithium-Ion Batteries and Supercapacitors (skeletontech.com)	Flywheels and Batteries – for acceleration	2023
Stationary	Dualflow ERC project	RFB storage with catalytic discharging unit, providing hydrogen for other stationary applications	2024
Stationary	ALMAGRID (Spanish national funding)	Hybrid LNMO + Zn-Air + Vanadium RFB	2023
Waterbone	NEMOSHIP (HEU)	Two types of Li-Ion batteries: HP and HE	2026

Waterborne	AENEAS (HORIZON-CL5-2022-D5-01-02-GA-101095902)	innovAtive ENErgy storage systems onboArd vesselS : Hybrid systems combining Solid State Batteries and Supercapacitors	2026
Waterborne	The Dutch Research Council (NWO) Funded Project: Maritime Batteries	Ship storage system as a heterogenous combination of LFP Solid State Battery (in development) and a traditional chemistry: NMC	2026
Waterborne	The Dutch Research Council (NWO) Funded Project: SEANERGETIC	Ship system expanded energy storage devices lifetime via AI-empowered control (SEANERGETIC) Fuel cells + Battery Hybrid	2026

This project has received funding from the European Union’s Horizon Europe
Research and Innovation Programme under Grant Agreement N. 101069676

Contact us

www.batterieseurope.eu
info@batterieseurope.eu