

White Paper

Sustainable hybrid ES for the European Clean Energy Transition: Unlocking the Potential application for hybrid ES



AUTHORS

Alessandra Tacca (ENI)
Alessandro Agostini (ENEA)
Chiara Busto (ENI)
Christina Wulf (FZJ)
Claudio Carbone (ENEA)
Federico Bresciani (ENI)
Friedrich Jasper (KIT)
Ganna Gladkykh (EERA)
Giovanni Tumminia (CNR)
Hüseyin Ersoy (KIT)
Jorge Salgado Beceiro (SINTEF)
Koroush Malek (FZJ)
Laura Sofia Mesa Estrada (KIT)
Linda Barelli (UNIPG)
Manfredi Picciotto Maniscalco (CNR)
Manuel Baumann (KIT)
Marcel Weil (KIT)
Marco Ferraro (CNR)

Martina Haase (KIT)
Maurizio Cellura (UNIPA)
Merve Erakca (KIT)
Patrick Stuhm (KIT)
Petra Zapp (FZJ)
Roland Hischer (EMPA)
Sarah Schmidt (SINTEF)
Sebastian Dickler (FZJ)
Sonia Longo (UNIPA)
Spyridon Pantelis (EERA)
Stefano Passerini (KIT)
Stephan Abermann (AIT)
Susan Taylor (EASE)
Tim Müller (KIT)
Tomás B. Ramos (NOVA)
Viera Pechancová (TBU)
Yannick Wimmer (AIT)
Yolanda Lechon (CIEMAT)

ACKNOWLEDGEMENT



StoRIES is an EU-funded project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 101036910.

DISCLAIMER

The sole responsibility for the content of this report lies with the authors. It does not necessarily reflect the opinion of the European Union. The European Commission is not responsible for any use that may be made of the information contained therein.

While this publication has been prepared with care, the authors and their employers provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained therein.

LIST OF CONTENTS

ABBREVIATIONS AND ACRONYMS	4
EXECUTIVE SUMMARY	5
1. INTRODUCTION	6
2. ENERGY STORAGE	8
Energy Storage overview	8
Role of hybrid energy storage technologies	11
3. SUSTAINABILITY ASSESSMENT OF ENERGY STORAGE	13
Motivation for sustainability assessment	13
StoRIES Approach to Sustainability	14
Sustainability Assessment methods overview	16
4. METHODOLOGY AND OVERVIEW	19
5. RECOMMENDATIONS FOR SUSTAINABILITY ASSESSMENT FOR HYBRID ENERGY STORAGE	21
Selection of KPIs and related methods	21
MCDA for Stakeholder involvement	23
The Business Sustainability Canvas Template	25
6. TAKE AWAYS FOR HESS SUSTAINABILITY ASSESSMENT	28
7. HESS MCDA USE CASE	30
Goal and Scope	30
Sustainability assessment example via MCDA	31
Performance matrix for storage evaluation	32
Results	34
Discussion	36
8. CONCLUSIONS AND NEXT STEPS	37
Recommendation for different stakeholder groups	38
Policy	38
Industry	38
Academia	39
Final remarks	39
9. ANNEXES	40
Annex 1	40
Annex 2	40
10. LITERATURE	54

ABBREVIATIONS AND ACRONYMS

AIT	Austrian Institute of Technology	LCA	Life Cycle Assessment
BES	Battery Energy Storage	LCC	Life Cycle Costing
BSCT	Business Sustainability Canvas Template	LCOE	Levelized Cost of Energy
BSC	Business Sustainability Canvas(es)	LCOS	Levelized Cost of Storage
BTM	Behind-the-Meter	LCSA	Life Cycle Sustainability Assessment
CAES	Compressed Air Energy Storage	Li-ion	Lithium-ion
CAPEX	Capital Expenditure	MCDA	Multi-Criteria Decision Analysis
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas	(MADM)	Multi-Attribute Decision-Making
CNR	Consiglio Nazionale delle Ricerche	MRIO	Multi-Regional Input-Output
CRMA	Critical Raw Materials Act	NPV	Net Present Value
DoC	Deck of Cards	NZE	Net-Zero Emissions by 2050 Scenario
E/P ratio	Energy to Power ratio	OPEX	Operational Expenditure
EERA	European Energy Research Alliance	P2A	Power-to-Ammonia
EMRIO	Extended Multi-Regional Input-Output Analysis	P2H	Power-to-Hydrogen
ENI	Ente Nazionale Idrocarburi	P2M	Power-to-Methane
EoL	End of Life	PHS	Pumped Hydro Storage
ES	Energy Storage	PV	Photovoltaics
ESG	Environmental, Social, and Governance	RED III	Renewable Energy Directive III
EU	European Union	SDGs	Sustainable Development Goals
FAIR	Findable, Accessible, Interoperable, Reusable	SET	Strategic Energy Technology Plan
FTM	Front-of-the-Meter	S-LCA	Social Life Cycle Assessment
HELDA	Helmholtz MCDA Tool	SMES	Superconducting Magnetic Energy Storage
HES	Hybrid Energy Storage	SRIA	Strategic Research and Innovation Agenda
HESS	Hybrid Energy Storage Systems	SROI	Social Return on Investment
IEA	International Energy Agency	SEIA	Social and Environmental Impact Assessment
IRR	Internal Rate of Return	TBL	Triple Bottom Line
JP	Joint Programme	UN	United Nations
KIT	Karlsruhe Institute of Technology	UNIPA	Università degli Studi di Palermo
KPI	Key Performance Indicator	VRFB	Vanadium Redox Flow Battery
KPI	Key Performance Indicator	WP	Work Package

EXECUTIVE SUMMARY

This white paper, a key output of the StoRIES project, presents a comprehensive framework for the sustainability assessment of Hybrid Energy Storage Systems (HES), positioning them as crucial enablers for Europe's clean energy transition. It translates complex technical and sustainability metrics into a clear, actionable guide for decision-makers, including policymakers, industry stakeholders, and researchers. The central thesis of HES is that by combining multiple energy storage technologies, HES can deliver superior performance, resilience, and cost-effectiveness compared to single-technology solutions, thereby unlocking the full potential of renewable energy sources.

The core of the paper is a harmonised sustainability assessment methodology grounded in the "Triple Bottom Line" (TBL) approach, which gives equal weight to environmental, economic, and social dimensions. This is operationalised through a multi-level set of Key Performance Indicators (KPIs) that evaluate a system's entire lifecycle, from raw material extraction to end-of-life recycling. The framework emphasises transparency and stakeholder involvement, recommending the use of Multi-Criteria Decision Analysis (MCDA) to navigate the inherent trade-offs between different sustainability objectives.

To demonstrate the practical application of this framework, the paper includes a detailed use case of an industrial energy hub. This example illustrates how to select relevant KPIs, engage stakeholders in weighting these criteria, and apply MCDA to arrive at a balanced and transparent decision. It shows how hybrid systems, such as a combination of batteries for rapid response and hydrogen for long-duration storage, can be optimised to meet specific application demands while minimising environmental impact and maximising economic viability.

Furthermore, the document introduces the Business Sustainability Canvas (BSC) as a tool to integrate these sustainability considerations directly into business model development. By extending the traditional business canvas to include environmental and social layers, it encourages a holistic approach to project planning, ensuring that sustainability is a core component of the value proposition, not an afterthought.

In conclusion, this white paper provides both a strategic vision and a practical toolkit for advancing HES in Europe. It argues that a systematic and inclusive approach to sustainability assessment is essential for de-risking investments, guiding policy, and accelerating the deployment of the flexible and resilient energy storage infrastructure needed to achieve a climate-neutral continent.

INTRODUCTION

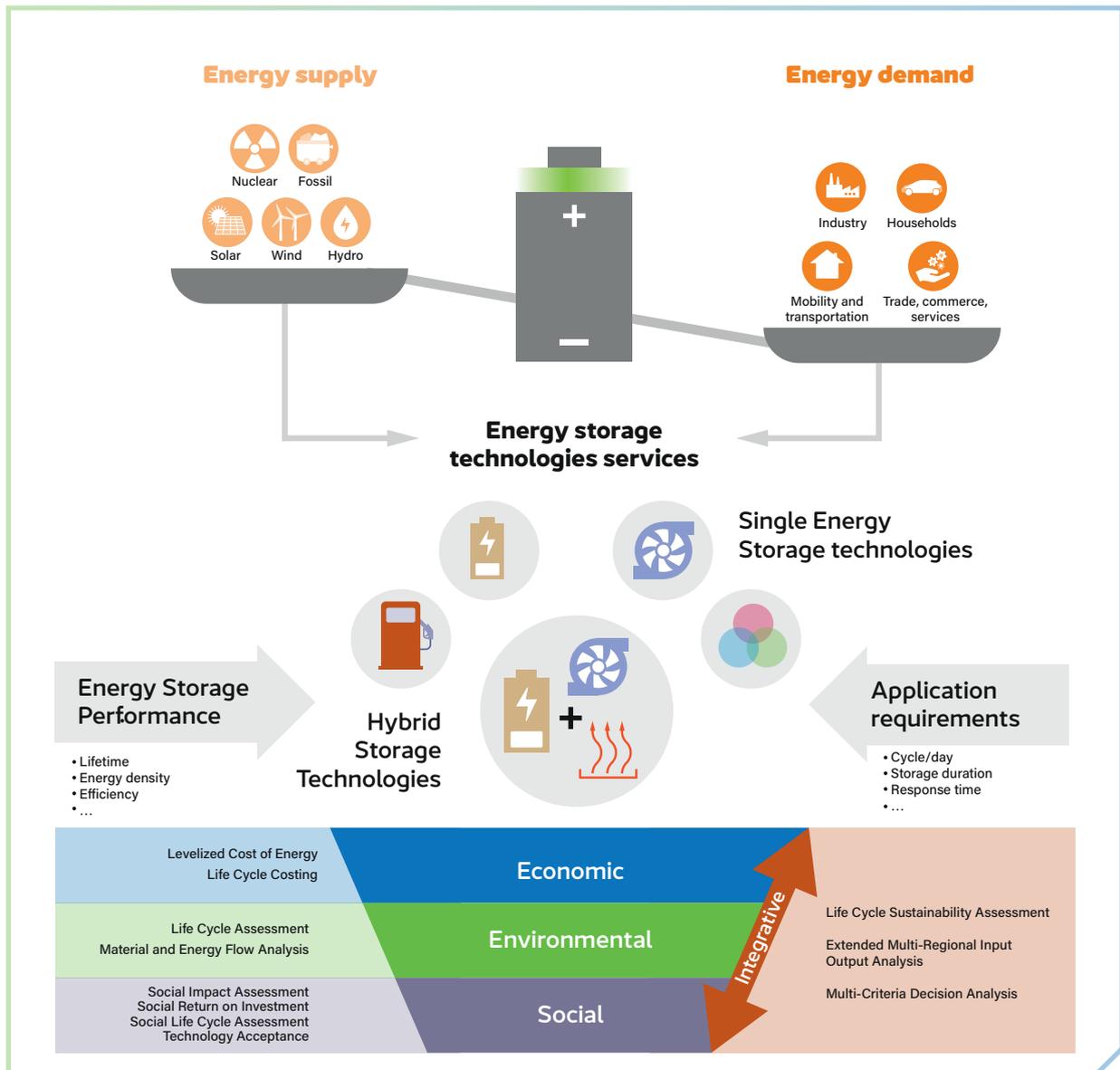


*The Sustainable Development Goals (SDGs) of the United Nations (UN) introduce a set of action plans towards a globally sustainable society, setting people, planet, prosperity, peace and partnership as core principles [1]. In this sense, providing clean and affordable energy (SDG 7) via the energy transition is expected to play a vital role towards a sustainable global society. Furthermore, progress in SDG 7 is anticipated to act as a catalyst for accelerated progress in other SDGs [2, 3]. The energy transition is a global challenge that requires massive efforts to roll out renewable energies on every scale, with increased supply duration using energy storage (ES) technologies with a significant global ramp-up in deployment between 2030-2050. The International Energy Agency's (IEA) Net-Zero Emissions by 2050 Scenario (NZE) envisions 7% reduction in the total energy supply between 2020-2030, with solar photovoltaics (PV) and wind turbines providing nearly 70% of the global electricity generation to limit the global mean temperature increase to 1.5 °C [4]. In line with renewable energy demand and required flexibility, the largest share of ES technologies for power networks belongs to pumped hydro storage (PHS) by 160 GW and is anticipated to grow moderately until 2030. Currently, battery energy storage (BES) accounts for 45 GW storage capacity (increased by 2,500% between 2015-2022), where Li-ion batteries account for 90% of the overall capacity additions [4]. Moreover, the NZE scenario requires globally an installed BES capacity of 4,200 GW by 2050 to meet the predicted storage demand [5]. In this scenario, Europe alone needs around 187 GW of ES capacities until 2030 aiming a further expansion to 600 GW by 2050 [6]. Furthermore, the rapid renewable build-out, grid constraints and periods of negative wholesale prices are driving the need for flexible, multi-vector storage. Hybridising complementary technologies, e.g., batteries for short-term response, thermal storage for heat shifting, and hydrogen for long-duration can lower system costs, reduce curtailment and strengthen resilience. The European Union is actively advancing HESS through the **European Green Deal** initiatives, the **Strategic Energy Technology (SET) Plan**, and targeted funding programs (e.g., StoRIES), which is addressed in depth in the SRIA [7]. However, while ES technologies can be considered as enabler of sustainable energy futures, their overall lifecycle can be strongly tied into unintended impacts on all three dimensions: economic, environmental, and social (with different skews depending on the technology) [8-10].*

Therefore, an incorporated implementation of social, economic, and environmental protection measures necessitates transdisciplinary perspectives based on reliable, transparent, reproducible, and accessible assessments. Such assessments in the field of ES and HESS might contribute to the development of sustainable ES materials, technologies, and concepts to enable a transition towards a sustainable energy system [11]. Attributing to the current academic and political debates, this white provides a comprehensive methodological overview of sustainability assessment methods applied for ES technologies capturing the whole lifecycle stages and impacts on the corresponding sustainability dimensions. The main audience of this review entails cross-disciplinary researchers in the field of sustainability, energy

storage and energy systems. Beyond academia, this compact white paper provides concise insights on methods and their abilities for the sustainability assessment of ES technologies for decision-making in an industrial (e.g., manufacturers, utility, system integrators) or policy-making context. Ultimately, this white paper should illustrate a base for facilitating a cross-disciplinary dialogue around sustainability issues based on the pictured assessment landscape and pinpointed drawbacks in the current practices.

Figure 1: Introductory figure, overview of three main sustainability assessment dimensions and corresponding method selection for ES technologies. Notice, the battery is representative for all energy storage technologies.



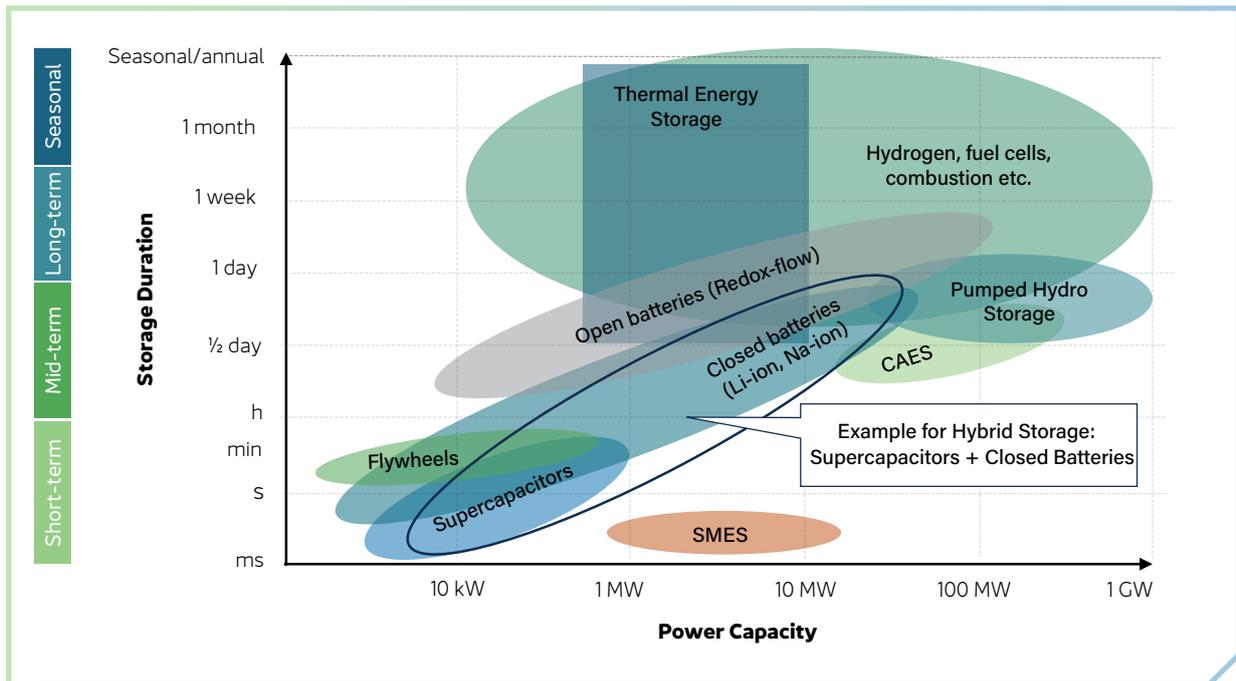
ENERGY STORAGE



Energy Storage overview

ES technologies play a crucial role in ensuring a secure power grid by providing services that uphold power quality and allow for a system-safe integration of renewables. In addition to power grid services, there is a need for introducing dense renewable energy carriers (i.e., storage media, renewable/carbon-neutral fuels) with long-term storage feasibility for the decarbonisation of sectors where currently the energy supply is covered by fossil fuels. On that matter, renewable electricity-based fuels (e.g., hydrogen, ammonia, methane) are expected to substitute conventional fuels where electrification of the heat supply or transport is not possible or feasible due to operational reasons. As a result, present-day ES technologies are designed and implemented to fulfil these services depending on their features across a range of storage applications, covering durations from short-term to long-term services. Figure 2 provides an overview of various ES technologies with distinct technical and technological characteristics, and applications, identifying relevant providers of corresponding services. Figure 3 provides an in depth overview of the different technologies in terms of technical specifications, the colour indicators (red, yellow, green) represent a qualitative comparison of different technical specifications. Grayed-out beacons imply 'no assessment possible' since the available data does not allow a direct comparison depending on the conversion path choices. As it can be concluded from Figure 2 and 3, single and hybrid ES technologies demonstrate distinct features (e.g., reaction time, charge/discharge profile, or energy-to-power ratio) for providing the services on various levels of the energy system (i.e., generation, transmission, and distribution) [12].

Figure 2: Overview of different ES technologies regarding applicable power capacities and storage durations (Based on D4.2)



Mechanical ES technologies, such as PHS and compressed air energy storage (CAES), are currently the most advanced and cost-effective options for short to mid-term ES applications. PHS stands out particularly due to its substantial capacity, long track record and long lifetime [13]. Nevertheless, there are technical, geographical, social, and ecological constraints in terms of feasible expansion capacities for PHS and CAES [14].

Chemical ES technologies, such as Power-to-H₂ (P2H), Power-to-Ammonia (P2A), and Power-to-Methane (P2M), are emerging concepts gaining prominence due to their high gravimetric energy density, long storage durations, and transportability [15]. In the context of long-term ES, techno-economic key performance indicators (KPIs) for decision-making revolve around capacity, flexibility, scalability, storage cost and efficiency [16]. Power-to-X technologies provide advantages in terms of capacity, flexibility, and scalability. However, existing and emerging concepts suffer from high costs due to low power-to-power conversion efficiency (20-40%) hindering their wide adoption [17].

Figure 3: Technical properties and service applications of energy storage technologies. Providers indicated in brackets means the service can be partly provided/benefited by the named provider/beneficiary [18].

		Mechanical				Chemical			Electrochemical					Electrical		Thermal				
		PHS	CAES	LAES	Flywheel	P2H	P2A	P2M	LIB	Ni-Cd	NaS	SIB	VRFB	LAB	SC	SMES	TCS	PCM	STES	
Technical specifications	Technology Readiness Level	9	5-8	7-8	9	6-9			9	9	9	6-7	7-9	9	9	5-8	4-7	1-8	5-9	
	Energy capacity	High	High	High	Low	High	High	High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Moderate	High	
	Power installed capacity	High	Moderate	Moderate	Low	High	High	High	Moderate	Moderate	Moderate	Moderate	High	Low	Low	Moderate	Moderate	Moderate	High	
	Storage duration	Moderate	Moderate	Moderate	Low	High	High	High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Low	Moderate	High	High	
	Efficiency	High	Moderate	Moderate	High	Low	No assessment	No assessment	High	High	High	High	High	High	High	High	High	High	High	
	Response time	Moderate	Low	Low	Moderate	Moderate	Moderate	Moderate	High	High	High	High	High	High	High	High	High	Low	Low	Moderate
	Cycling or lifetime	High	High	High	High	Moderate	High	High	High	Moderate	Moderate	Moderate	High	Moderate	High	High	Moderate	High	High	
Services	Generation Support & Bulk Storage	E, T				E			T, P, I	PO, T						E, (D), I				
	Transmission Infrastructure	E, T			T				D, T					T						
	Distribution Infrastructure	D				E			D, A	A, T, PtX, I						E, (D), I				
	Ancillary	E, D				E			D, P, Ic	PO, D					E, D	E, P, (D), I				
	BTM Customer Energy Management		Ic, A, D						D, P, A, I					I, D	E, P, (D), I					

Storage technologies PHS = Pumped hydro storage CAES = Compressed air energy storage LAES = Liquid air energy storage P2H = Power-to-hydrogen P2A = Power-to-ammonia P2M = Power-to-methane LIB = Lithium-ion battery Ni-Cd = Nickel-cadmium battery NaS = Sodium-sulfur battery	SIB = Sodium-ion battery VRFB = Vanadium redox flow battery LAB = Lead-acid battery SC = Supercapacitor SMES = Superconducting magnetic energy storage TCS = Thermo-chemical energy storage PCM = Phase changing material STES = Sensible thermal energy storage	Evaluation scheme ● High ● Moderate ● Low ● No assessment available	Actors A = Aggregator D = Distribution system operator E = Energy supplier I = Industrial actor Ic = Industrial client P = Private actor PO = Power plant operator PtX = Power plant operator including PtX T = Transmission system operator
--	---	--	--

Electrochemical ES technologies such as lithium and sodium ion or redox flow batteries demonstrate lower performance characteristics in terms of energy density, lifespan, and storage duration due to technological constraints, although these can vary significantly depending on the cell chemistry. Overall, their rapid reaction times, high conversion efficiencies (~90%), scalability, and reduced costs make them highly suitable for short- and mid-term stationary applications. Moreover, they can be situated both in front-of-the-meter (FTM) and behind-the-meter (BTM), encompassing a wide range of applications [19]. This comes also true for flywheels, which are suitable for short term applications.

Electrical ES technologies such as supercapacitors, offer increased possibilities for transmission applications due to their quick response time (milliseconds) and high power density, facilitating the maintenance of power quality [20].

Thermal ES technologies, various heat storage technologies (sensible, latent, and thermochemical) provide advantages, particularly in concentrated solar power plants, thanks to their high efficiency. These technologies offer potential for cross-sectoral ES services, depending on the operational temperature range [21].

Hybrid Energy Storage Technologies. In a nutshell, no single ES technology can provide all desired characteristics to act as a single solution for multiple services needed. Consequently, hybrid ES concepts are being explored, where the limitations of one ES technology are compensated by another, making

them complementary (e.g., combination of the extended lifespan and low cost of Vanadium Redox Flow Batteries (VRFB) with the rapid response and high energy density of Li-ion batteries) [22]. Thus, hybrid ES technologies expand the range of services offered by leveraging improved power and energy capacities via service stacking, providing overall improved performance [23]. All in all, the provided technological overview shows that there is at least one technology alternative technically capable of providing each service.

Role of hybrid energy storage technologies

It can be concluded that there is no single technology which can act as a one-for-all solution considering the provided technological overview and discussed service-related aspects in the previous chapters. The development of HES is being promoted by the European Union, for example within the framework of the European Green Deal initiatives, the Strategic Energy Technology (SET) Plan and specific funding projects (e.g. StoRIES). HES are considered “key enablers” of a climate-neutral, resilient energy infrastructure, as they link sectors, connect markets and unlock the full potential of renewable energies [7]. Fundamentally, hybridisation is the combination of two or more inherent features to meet specific needs. Within the StoRIES project, an overarching definition has been generated after some discussion rounds, which resulted in the following definition:

“Hybridisation of ES refers to the utilization of two or more ES technologies together on either a system, device, or material level to provide technical and economic advantages beyond what any single ES technologies can provide, also considering the sustainability and reliability over the lifetime of the hybridized solution.”

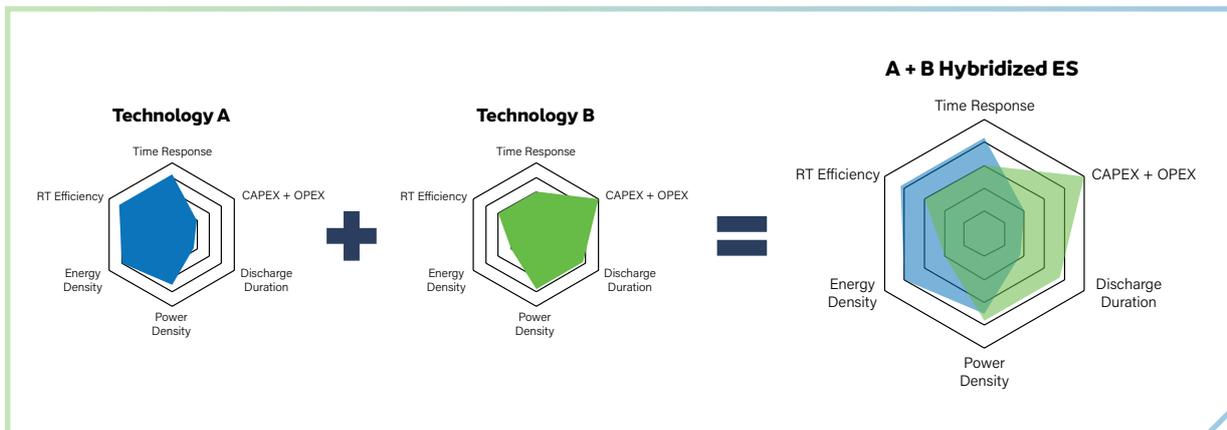
As it is referred in the presented definition, hybridisation of ES technologies can be carried out at different levels. Expecting that hybridisation does not serve only as a mean to enhance techno-economics, but also provide benefits beyond that. For instance, fuel reduction, emission reduction, and improvements in energy and reliability efficiency are some examples to be named. The development of a HESS is a problem-driven task to solve a certain problem and not a purpose on itself. Hybridisation can provide the following benefits:

- **Optimised system design:** Avoidance of over-dimensioning by smartly combining components.
- **Longer lifetime:** Reduced stress on individual storage units through optimised hybrid operation (e.g., using the most suitable device for a given load).
- **Lower life-cycle costs:** Combining cost-effective components reduces total life-cycle cost.
- **Multiple services:** Concurrent provision of services, over multiple storage timeframes, allowing one hybrid to cover several use cases (e.g., frequency control *and* energy shifting).
- **Sector coupling and flexibility:** Linking electricity, heat, and mobility enables versatile applications and increases system flexibility.
- **Sustainability gains:** Overall carbon footprints can fall and resources be conserved by leveraging each technology’s strengths and offsetting weaknesses. For example, a technology relying on critical raw materials (e.g., lithium-ion batteries) can be complemented by one that does not (e.g., flywheels).

As mentioned earlier, technological features of a hybrid system, including HESS must be matched and optimised for a specific problem. Such optimisation depends on the level of the targeted application (e.g., utility-scale, decentralised systems, industrial applications, transport systems, grid services, trans-sectoral, high-temperature industrial heat and pressure, production of chemical feedstock) in different fields. Besides combining technologies physically, hybridisation through control strategies is another way of optimising the proposed solution. However, it should be noted that the implementation of optimised control strategies is an inseparable part of hybridisation. On the device level many hybridisation configurations can be designated by implementing optimised control strategies to achieve the goal of hybridi-

sation. The given spider chart in Figure 4 illustrates an example of hybridisation at device level between batteries and supercapacitors. As it can be concluded considering the technical performance comparison, such hybridisation results in significant improvements in terms of power density, specific power, cycle lifetime, and energy costs thanks to high-power applicability of supercapacitors.

Figure 4: Spider chart displaying KPIs of a battery-supercapacitor hybrid application [24].



These advantages explain why HES are attractive for certain applications for Europe right now: they improve the technical and economic feasibility of the energy transition and help deliver European climate and energy targets (e.g., at least 55% GHG reduction by 2030 and a high share of renewables). In line with this, a systematic sustainability assessment of HES is essential to support sound decisions on technology choice, investment, and policy design. The sections below outline the relevant sustainability goals and assessment approaches, and how decision-makers and project developers can practically evaluate the sustainability of HES.

SUSTAINABILITY ASSESSMENT OF ENERGY STORAGE



3

Motivation for sustainability assessment

An ideal assessment for sustainable ES systems requires an equilibrated consideration of the interplay and interdependency of economic, environmental, and social aspects [25]. Nevertheless, ES decision-making processes have been significantly dominated by economics mainly due to a narrowed-down scope in the decision-contexts (i.e., solely techno-economics) and a lack of diverse stakeholder engagement. While acknowledging the necessity of profitable businesses, there is a growing demand to define sustainability frameworks that strike a balance and safeguard the interests of all stakeholders. Furthermore, considering the actual cost of decisions beyond monetary terms, one can conclude that cost-effectiveness cannot be realised properly without adequate reasoning of environmental and social costs posing a complex challenge in operationalisation of sustainability assessments that is being widely discussed in academia [26].

To this end, approaches such as the triple-bottom-line (TBL) model [27], and the environmental, social and governance (ESG) framework have been utilised to bridge all sustainability dimensions during operationalisation [28]. The TBL model claims that sustainable development can only be achieved through simultaneous and equal realisation of environmental, economic, and social goals [29]. The ESG framework embodies criteria and framework conditions for the consideration of the environmental, social and governance aspects within private and public organisations, and NGOs, academia, or business. From this aspect, ESG provides extended guidance for implementing the TBL model. Considering that some success stories provide evidence for the effective realisation of the TBL considerations using ESG measures, tremendous efforts are required for TBL's wide acceptance.

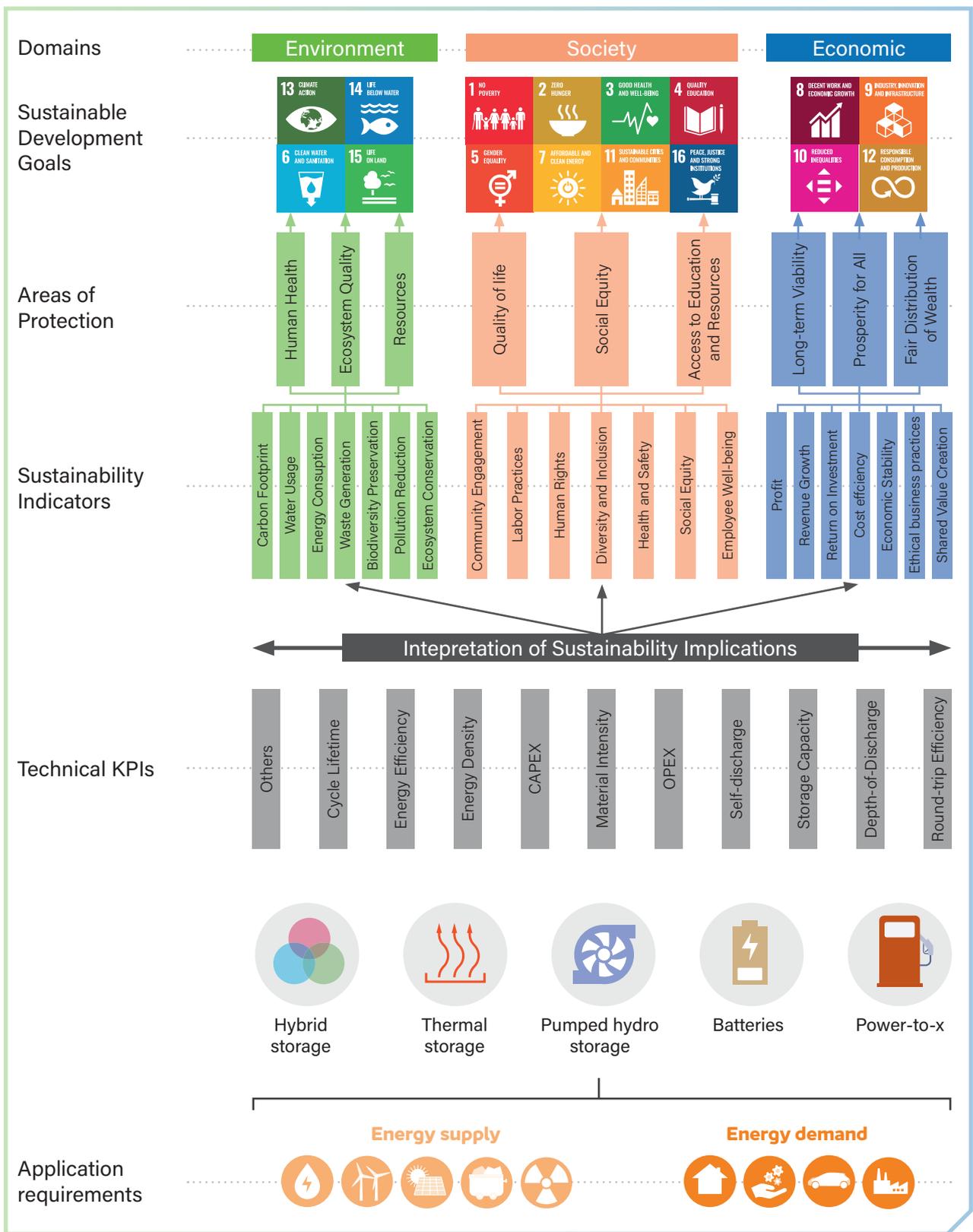
Undoubtedly, making continuous conceptual refinements are necessary, and will contribute to this goal. However, it is important that sustainability assessments are hammered out considering a feasible time scale, transparency, and comparability [30]. For ES technologies, various sustainability assessment methods are available considering the sustainability dimensions. Additionally, there are overlaps on assessment scopes and core stakeholders underline the interdependencies of the indicated sustainability dimensions. It can be concluded that a clear separation of these dimensions is hardly possible and not

useful for addressing overall sustainability. Integrative methods are often resorted for capturing (to a certain degree) the interdependencies via consideration of multiple sustainability dimensions. It's worth noting that the inclusion of institution/governance as a fourth dimension is an ongoing dispute, alongside the previously mentioned pillars of sustainability [31]. However, this dimension is not separately considered within the context of this white paper.

StoRIES Approach to Sustainability

Within StoRIES project a framework was developed for assessing the sustainability of energy storage systems, specifically HESS, via the SRIA 2025, Roadmap 2025, Deliverables D4.1 and D4.2, Workshop series and hybrid energy storage book [7] [103]. The central message of StoRIES is that sustainability must be understood in a multidimensional way: ecological, economic and social goals are equally important and must be implemented simultaneously in order to achieve sustainability. This TBL concept, consideration of environmental, economic and social aspects, forms the basis of the sustainability goals identified within StoRIES. In addition, StoRIES draws on the ESG framework, which provides concrete criteria and guidelines for anchoring the TBL dimensions in organisations and projects. In this way, StoRIES ensures that governance aspects (such as transparency, responsibilities and stakeholder participation) are included in the sustainability assessment, an aspect that is often discussed as a fourth dimension but has been integrated into the three main pillars in the StoRIES context. From this different sustainability indicators can be derived, which in turn can be allocated to the three different sustainability domains and areas of protection. The performance of these indicators is bound to the technical KPIs and the application requirements of ES, as shown in Figure 5.

Figure 5: TBL Approach considering the SDGs and different technical KPIs for energy storage technologies



The development of the framework is guided by the overarching goals of the European Green Deal and the UN Agenda 2030. Specifically, this means maximising HES contributions to climate neutrality, resource conservation and social justice. European targets, e.g. RED III (Renewable Energy Directive) with a target of 42.5% renewable energy by 2030, or the Energy Efficiency Directive, set the framework within which HES contribute to achieving these targets (e.g. by increasing the share of renewable energy and intelligent demand management). In addition, an important aspect is to decouple growth from resource consumption: dependence on critical raw materials is to be reduced, among other things through circular strategies (reuse, recycling) and material substitution [7, 32]. It is emphasised that future storage technologies will use fewer toxic and critical materials and that Europe will diversify its supply chains – in line with the Critical Raw Materials Act (CRMA) proposed in 2023 and the new EU Battery Regulation. Socio-economic goals such as local value creation, employment and acceptance are also addressed: HES should help to achieve a *just* energy transition (keyword: *fair transition*) by, for example, promoting new business models for citizen energy, industrial competitiveness in Europe and social inclusion [7, 33].

To make these goals measurable and achievable, StoRIES proposes an integrated sustainability assessment approach; an assessment framework as a “*common base*” for environmental, techno-economic and socio-economic assessments. This framework combines established methods of life cycle assessment (LCA), life cycle costing (LCC) and social LCA into a holistic method such as life cycle sustainability assessment (LCSA). LCSA thus integrates environmental, cost and social analyses across the entire life cycle of a system. StoRIES emphasises that LCSA reveals all trade-offs in an unbiased manner, e.g. when an option is ecologically advantageous but more expensive, or economically favourable but associated with social disadvantages. In addition to LCSA, numerous other methods were reviewed (e.g. multi-criteria decision analysis, material flow analyses, technical key figure comparisons). The core elements of each approach, indicators, system boundaries, data requirements, stakeholder roles were identified in StoRIES to provide a blueprint for future HES assessments and will be presented in the following for the single dimensions.

Sustainability Assessment methods overview

The key findings of any sustainability assessment are usually communicated using KPIs. KPIs are *measurable metrics* or derived evaluation variables that quantify the status or success in relation to a specific criterion. Sustainability indicators, KPI values themselves are determined using appropriate methods which are often oriented towards on sustainability dimension. Economic, environmental, and social assessments are essential for evaluating the sustainability of ES technologies. Economic evaluations consider CAPEX, OPEX, and financing methods such as NPV, IRR, LCC, and LCOE, while also integrating broader socio-economic benefits through cost-benefit and risk-benefit analyses. Environmental assessments, primarily using LCA, MFA, MRIO, circular economy, and criticality studies, address lifecycle impacts, resource flows, and regulatory compliance (e.g., EU Battery Directive), though challenges remain around data and system boundaries. Social assessments, using tools such as S-LCA, SROI, SIA, and SEIA, explore impacts on wellbeing, labour, communities, and stakeholder acceptance, recognising that public perception and behavioural responses can significantly influence project success. Together, these methods enable a holistic appraisal of ES technologies, balancing economic viability, environmental responsibility, and social acceptance to support the energy transition.

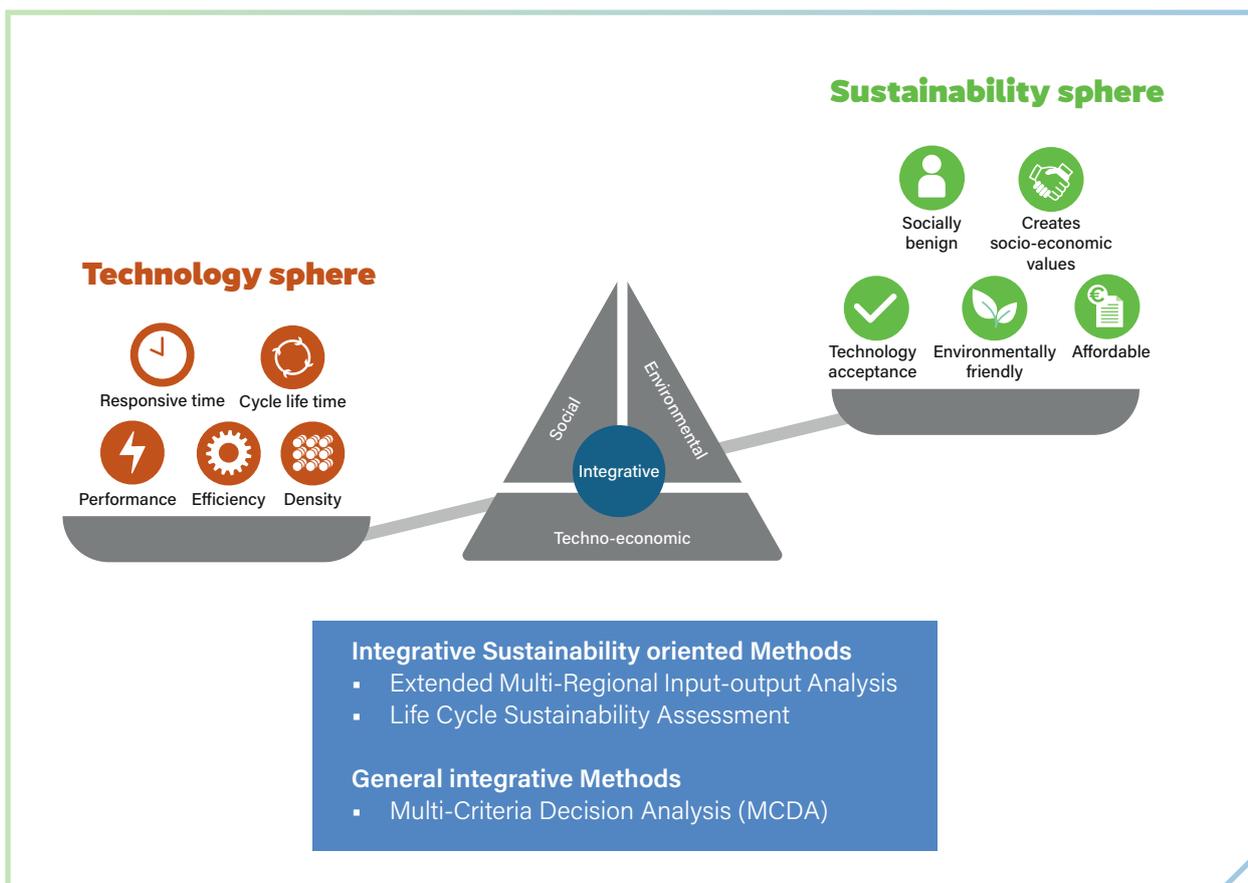
These methods are based on the authors’ elaboration use cases for each sustainability dimension and integrative approaches are selected and reviewed in frame of D4.2, serving as a baseline for the present publication [24, 34–74].

Considering only one dimension can be misleading for decision-making discussions in ES technology selection context, since there is no perfect ES technology that is suitable for all applications. Furthermore, if interdependencies between different sustainability dimensions are not considered integrally,

achieved improvement in one dimension can result in unintended impacts in another (i.e., burden shifting). Hence, a trade-off often must be found among different criteria (e.g., LCOE vs. carbon footprint). The main principle when conducting **integrated assessments** is to improve decision-making by combining analytical methods and using operations research methods to consider multiple dimensions, their interrelation and related impacts leading in a more comprehensive evaluation. Nevertheless, the interpretation and communication of results from integrated assessments vary. This is because the interdependencies, decision attributes, and objectives significantly influence the decisions in diverse ways throughout the decision-making process. In practice, the LCSA framework and Extended Multi-Regional Input-output Analysis (EMRIO) are the most commonly used approaches for multidimensional assessment of ES technologies, supported by Multi-Criteria Decision Analysis (MCDA) [68].

LCSA is a recognised framework that takes into account the environmental, economic, and social dimensions of a product, process, or service. This is achieved using LCA, LCC, and S-LCA methods, all under a unified goal and scope definition [75–81]. Additionally, the integration of circularity and criticality into the LCSA framework has been recently recognised as crucial, considering the growing global supply risk and import reliance [82]. It adheres to the conventional LCA framework in an iterative manner, incorporating an additional step that involves the presentation of aggregated scores. In this regard, LCSA serves as an indicative approach for decision-making, contingent upon the quality of the assessments, despite reports of shortcomings in the effective communication of LCSA results [83]. However, here it is of utmost importance that each perspective entails all relevant lifecycle phases, particularly the end-of-life phase. The latter can simply reshuffle cards in terms of environmental impact and resource use.

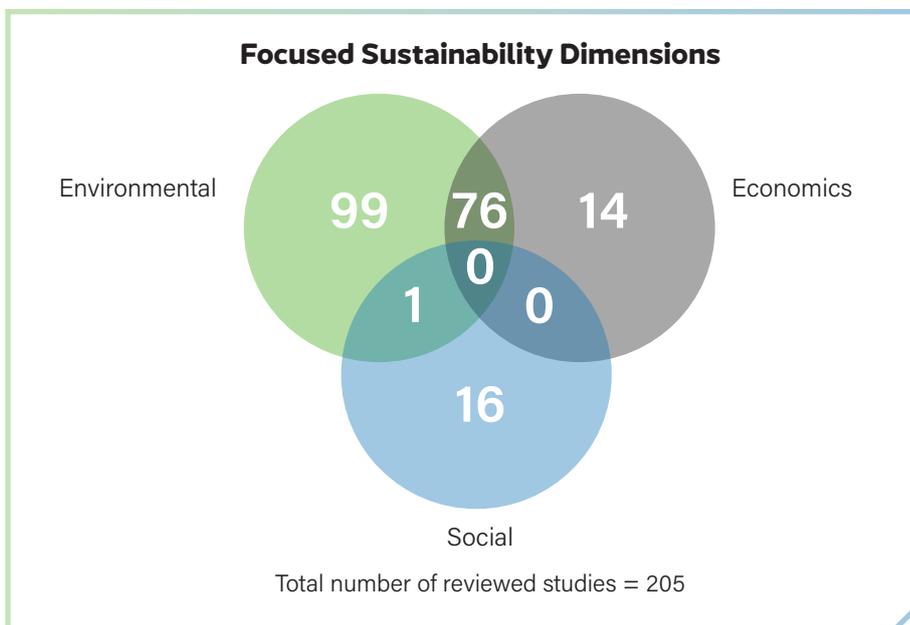
Figure 6: integrative methods for sustainability assessment of energy storage technologies.



MCDAs are used as an approach for dealing with decision problems including multiple criteria, stakeholders, and potential alternatives. In the ES context, a subset of studies applying MCDA mostly focuses on multi-attribute decision-making (MADM) methods as they are suitable for comparing concrete technology alternatives. In this way, the MCDA serves to structure a problem, or to rank and sort alternatives. The MCDA is carried out in two overlapping phases, namely, construction and exploitation. The construction phase covers goal, scope and alternatives definition, identification and selection of criteria, selection of MADM methods, and stakeholder interface creation. The exploitation phase facilitates criteria performance measurements, weights elicitation, criteria aggregation, and results comparison. The exploitation phase can be carried out using several methods, which can be divided into compensatory (e.g., analytic hierarchy process – AHP) or outranking methods (e.g., Preference ranking organisation method for enrichment evaluation – PROMETHEE) [84, 85]. MCDA allows for a comprehensive and iterative engagement of stakeholders in both phases [86]. In any case, an MCDA must be carried out in a careful way assuring the comparability of alternatives, to avoid non-practical academic exercises without a real-world context [87].

EMRIO, an extension of MRIO, integrates socio-economic and environmental indicators into the input-output matrix, enabling a multidimensional assessment of sustainability in macro-economic terms [88]. Common socio-economic indicators include value-added and employment, while environmental impacts often focus on global warming, with options for other categories like acidification or land use. The social dimension is addressed through qualitative and quantitative indicators [89]. EMRIO also supports macro-level analyses, such as supplier governance risks, multiplier effects, and spill-over impacts [90]. The review published recently [18] showed that there are no studies available that consider all dimensions in a comprehensive way as shown in Figure 7, implying that there is a strong need for such studies in the field of HESS.

Figure 7: Considered studies, distribution of focused sustainability dimensions [18]



METHODOLOGY AND OVERVIEW

4

Within the StoRIES project great importance to the practical applicability of the methods was given. For this reason, D4.2 [102] provides decision-making aids, e.g. a decision tree for method selection and hybridisation decisions, as well as sample templates such as a *Business Sustainability Canvas (BSC)* for linking assessment results with business model development. The approaches were validated through **workshops** with stakeholders (see Table 1), for example, an interactive StoRIES workshop that identified and weighted the most important sustainability KPIs for HES together with experts and users. StoRIES thus pursues a participatory understanding of assessment: technical expertise should be combined with the perspectives of various stakeholders (industry, politics, the public) in order to establish common sustainability definitions and criteria for HES. In summary, the StoRIES recommendations for sustainability assessment can be characterised as follows:

- **Holistic:** Consider the environment, economy and social aspects equally (TBL principle)
- **Standardised:** Define uniform *key performance indicators (KPIs)* that apply to all storage technologies (e.g. carbon footprint, levelised cost of storage, acceptance indicators)
- **Life cycle-oriented:** Assessment across *the entire life cycle*, from raw material extraction to operation to EoL (end of life) – to avoid shifting environmental burdens
- **Relevant to decision-making:** Results should be directly incorporated into **decision-making processes** (e.g. through MCDA and canvas models) to support technology selection, investments and policies based on sustainability criteria
- **Data-driven and transparent:** Establishment of **open data platforms** and application of FAIR principles to create robust and comparable data bases for all dimensions

The next section presents a structured guide on how to carry out a sustainability assessment for HESS step by step, based on these guidelines.

This white paper has been developed within the framework of the **StoRIES project**, through the collaborative efforts of researchers, industry representatives, and institutional stakeholders across Europe. The white paper takes due consideration of other StoRIES publications, such as: D.4.1 "*Guideline for collection and access to FAIR and open data for environmental, techno-economic and socio-economic Assessments*"; D. 4.2. "*Common base for environmental, techno-economic and socio-economic assessment to un-lock the potential applications for hybrid ES (HES) systems*", the **Sustainability Key Performance Indicators (KPIs)** and Assessment. It complements the StoRIES D. 4.2, and key documents such as the StoRIES Roadmap and SRIA.

Table 1: Overview of the three interconnected and interactive workshops

Workshop	Date and Venue	Goal	Participants	Outcome
Workshop #1 "FAIR and open data for environmental, techno-economic and socio-economic assessments"	Online (Pandemic) 27 October 2022	Discuss relevant KPIs and data handling	45 International participants covering different branches of sustainability assessment	Challenges in data collection and handling
Workshop #2 "Establishing a Unified Framework for Assessing Sustainability to Unleash the Potential of Hybrid Energy Storage Systems" (M24),	held during the HYBRID ENERGY STORAGE DAYS' 4-6 December 2023, Vienna	Gather a common base for sustainability assessment of ES with general, technology agnostic use cases to test the MCDA approach, KPIs lists and to identify overall challenges. And stakeholder preferences. The use cases were: <ul style="list-style-type: none"> ▪ short term energy storage use ▪ Long Term Energy Storage use 	44 Experts and members from EERA JP Energy Storage, STORIES and external members	Validation and improvement of the Stakeholder interaction and MCDA, Joint KPIs and weights
Workshop #3 "Sustainable hybrid ES for the European Clean Energy Transition" (M36)	Held during the StoRIES Project and EERA Joint Programme Energy Storage, 19 th of Nov 2024, Brussels	Apply the Business Canvas Template and MCDA to specific use cases and KPIs <ul style="list-style-type: none"> ▪ Emergency Power Backup for Critical Infrastructure ▪ Residential and Commercial Microgrids ▪ Seasonal Energy Storage for District Energy Systems ▪ Remote, Off-Grid Industrial Operations 	23: Experts from EERA and STORIES members	Testing of the MCDA and Business Canvas template approach.

The **Case Studies and Method input papers and Sustainability Guideline** draw upon extensive contributions from experts who co-authored the D 4.2 and the workshops reported in Table 1. Furthermore, the author group published an exhaustive review publication of applied sustainability assessment methods in the field of sustainability and energy storage in the Journal Sustainable Energy and Fuels of the Royal Society of Chemistry. Also, two publications for the Assessment of different storage Technologies based on the outcome of Workshops 2 and 3 are being prepared. A collection of 17 case studies published in the book [103] has been supported in line of the activity, which in turn was considered in the development of this white paper.

Through this collaborative, continuous multi-stakeholder process, the white paper presents a robust and comprehensive document to guide future sustainability assessment methods and applications for hybrid energy storage across Europe.

RECOMMENDATIONS FOR SUSTAINABILITY ASSESSMENT FOR HYBRID ENERGY STORAGE



The following guide provides a structured approach to assess the sustainability of HESS. It is based on the recommendations from StoRIES Deliverable 4.2 [102], the SRIA [7] and the Roadmap [33] and the workshop series. The section wraps up and extends the content from the named works. As such it is intended to provide a practical framework for users, from researchers, project developers to policy makers. The steps include defining objectives and scope, determining system boundaries, selecting suitable KPIs (at system vs. application level), aggregation logic for hybrid systems, stakeholder involvement (including MCDA), use of the triple-layer business canvas, and development of a data strategy according to FAIR. The principles are linked to a use case to provide practical context of the following steps.

Selection of KPIs and related methods

In the case of HES, KPIs must be carefully selected in order to reflect both the performance of the system itself (*system level*) and the added value in the application (*application level*) [32]. StoRIES recommends a multi-level KPI approach: first, general KPIs for energy storage were compiled across technical, economic, ecological and social dimensions; then, it was examined which of these are particularly relevant for hybrid systems and how they differ depending on the technology and application. An overview of identified KPIs in frame of StoRIES, their objective, used indicators, preference direction, description and level (application level=App and system Level=Syst) is provided in Table 2. Of course, the selection of KPIs has to be conducted depending on a certain context.

Table 2: Examples of KPIs at system and application level identified

Objective	Sustainability KPI	Indicators	Preference direction of KPI	Description	KPI Level
Positive public perception of energy technologies	Safety perception and public trust	Safety perception (qualitative)	max	Maximizing safety perception of ES technologies has a significant impact on their acceptance, adoption, and success in the market.	App
	Visual impact	Visual impact (qualitative)	min	Minimize the visual impact that the installation of the ES technology and complementary components may have on its surroundings, particularly in terms of aesthetic perception by the public.	App
Sustainable and circular value chain	EU production share in the value chain	%	max	Increasing the EU production share in the value chain of ES technologies is important to:	Sys
				-Maintain the EU as global centre for innovation and competitiveness in the ES sector.	
				-Strengthen Europe's resilience and strategic autonomy in the ES sector. -Support the creation & retention of skilled jobs in the EU.	
Circularity	How many times can components and/or materials be reused?	max	Maximize circularity of materials and components. At the end of their life, they should be reused, remanufactured or recycled to return valuable materials to the economy.	Sys	
Critical raw materials	Fraction/amount of critical raw materials used in the device	min	Minimization/elimination of critical raw materials is relevant to cost, availability and scale-up of ES technologies.	Sys	
Technical performance and durability	Efficiency	%	max	Maximize the round trip efficiency to minimize energy losses , maximize usable energy stored and retrieved.	Sys
	Durability	Years or full equivalent cycles	max	Maximizing durability refers to slowing the rate of efficiency degradation, component corrosion, and/or capacity loss.	Sys
	Distribution network	Infrastructure available to transport/distribute stored energy	max	Maximize the use of existing infrastructure such as pipelines, tanks, and terminals, reduces investments and time , and can avoid opposition from local communities concerned about environmental and safety risks.	Sys
Carbon neutral technologies	CO₂ footprint	kg CO ₂ eq / kWh	min	Minimize/avoid greenhouse gas emissions throughout the life cycle of the ES technology (i.e., raw material supply, construction, transportation, operation and end-of-life disposal) to prevent the effects of global warming and climate change.	App

Good health and wellbeing	Impact on human health	Human toxicity, cancer effects	min	Minimize/avoid health impacts on workers and local communities due to the emission of toxic gases, effluents and harmful elements (throughout the life cycle of the ES technology).	App
Environmental friendly technologies	Ecosystems impact	Human toxicity, non-cancer effects Ionizing radiation Particulate matter Marine eutrophication Ozone depletion Terrestrial eutrophication Acidification Freshwater ecotoxicity Freshwater eutrophication	min	Minimize the impact of the ES technology on the health and functioning of ecosystems throughout its life cycle.	App
Affordable renewable energy	CAPEX	CAPEX (system) (€/kW)	min	Minimize investment costs of ES technologies in the deployment of large projects would attract more investors and promote their adoption.	App
	LCOS	LCOS (€/kWh)	min	Minimize the cost per unit of electricity stored to make ES technologies more competitive. LCOS is calculated by dividing the investment, operation and maintenance (O&M), recharging, and end-of-life costs by the electricity discharged during the investment period and discounting them to the same reference date.	App

When selecting KPIs, it is essential to identify which level each KPI addresses. At the system level, the main focus is on measuring the technological performance and efficiency of the hybrid system, while at the application level, the focus is on the sustainability benefits in the specific application case. StORIES has shown that the *relevance of individual KPIs depends heavily on the specific hybridisation case, technology, application and services provided* influence which key figures are decisive. Therefore, when setting up the KPI set, one should always ask: *“Does this indicator contribute to answering the objective of the evaluation?”*. As mentioned before, KPIs are derived from different methods: technical KPIs often come from simulations, manufacturer specifications or test data; economic KPIs from cost models (discounted cash flows, LCOE calculations, etc.); ecological KPIs from LCA databases and calculations (e.g. CO₂ balance via LCA using Ecoinvent data); social KPIs may come from databases (Social Hotspot Database) using s-LCA or stakeholder surveys. It is important to document the data sources and calculation methods for each KPI to ensure transparency.

MCDA for Stakeholder involvement

Sustainability is, by its very nature, a value-laden, stakeholder-specific concept, different interest groups may have different priorities (e.g. climate protection vs. costs vs. local acceptance). Therefore, stakeholder involvement is a central element of a comprehensive HES assessment. StORIES emphasises that relevant actors, technology developers, investors, political decision-makers, end users, citizens, should participate in the assessment process in an appropriate manner. Participation can take various forms:

- **Inform:** Stakeholders are informed about the objectives, criteria and results of the assessment (transparency).

- **Consultation:** Stakeholders' opinions and preferences are sought, e.g. in workshops or surveys (participatory input).
- **Involvement/collaboration:** Relevant groups actively participate in the design of the assessment – for example, in the **selection of criteria, weighting of criteria** or interpretation of results. This was practised in the StoRIES workshops, in which experts and stakeholders e.g. jointly prioritised indicators.

The selection of *which* stakeholders are involved depends on the system: in the case of an industrial HES, for example, it would be operators, energy suppliers, possibly residents (if emissions/noise are relevant), regulators (grid connection issues), etc. In the case of research projects, other research partners may also be involved. It is important to consider the legitimacy of the stakeholders, i.e. to involve those who are affected by or have an influence on the project. The challenge is to find the *right balance*: too many participants can delay the process, too few can lead to blind spots.

A proven approach to structuring stakeholder preferences is MCDA. MCDA provides a framework for bringing together different KPIs (which have different dimensions and units) by assigning *weights* by stakeholders. Specifically, this works as follows:

1. **Establish criteria:** A catalogue of criteria is created from the KPIs (see previous section) – e.g. *environmental criteria* (represented by KPI CO₂, pollutant emissions), economic criteria (KPI LCOS, NPV), *technical criteria* (reliability, efficiency), etc. These can also be grouped (it is better to weight 5–10 grouped criteria than 30 individual KPIs).
2. **Weighting by stakeholders:** Representatives of the stakeholder groups weight the criteria according to importance. This can be done by awarding points, pair comparisons or other methods. In the StoRIES workshop, amongst other, the DoC *weighting method* was used, in which participants sorted and weighted KPIs in a group exercise. For this, transparent moderation is important, e.g. everyone should understand what the criteria mean.
3. **Evaluation of alternatives:** If there are different HES alternatives to choose from (alternative A vs. B vs. C), they are now evaluated for each criterion (e.g. in the form of utility values or rankings per KPI). If there is only one solution and its sustainability is to be measured “absolutely”, target specifications or reference values can also be used for comparison.
4. **Aggregate:** The MCDA method calculates the evaluations with the weightings and provides a total utility value for each alternative (or shows the fulfilment of each criterion in absolute terms). This reveals *which solution performs best including all criteria* and where compromises lie.
5. **Sensitivity analysis:** It is advisable to test the results when the weights vary, this allows you to see e.g. whether different stakeholder priorities would result in different decisions.

MCDA allows to make trade-offs explicit: stakeholders can see, for example, that an alternative with minimally better environmental values would be significantly more expensive, and can then discuss whether the added sustainability is worth the additional cost from their point of view. The StoRIES experience shows that different groups sometimes weigh factors differently (e.g. NGOs focus more on the environment, industry more on economic efficiency). One advantage of the MCDA process is that it reveals these differences and can thus promote consensus building by discussing the differences. In the end, for example, there may be a woven compromise that is represented in the weightings of all.

Please note

Not every sustainability assessment results in an MCDA. If the goal is purely a benchmark study (e.g. to identify the carbon footprint, LCOS and jobs of a system), weighting and aggregation is not necessarily required – the reader then makes the decision at their own discretion. However, MCDA always makes sense when several alternatives are to be compared according to several criteria and a selection is to be made (classic decision problem). In a white paper for decision-makers, it is helpful to at least introduce the *concept* of MCDA so that users know how to interpret the diverse results.

Overall, stakeholder involvement ensures that the evaluation is holistic and legitimate: all relevant perspectives are taken into account, the synthesis of results (MCDA) is transparent and comprehensible, and the final decision is more likely to be accepted by those involved because they were taken into account in the process. This significantly increases the feasibility of the proposed sustainable solution.

Within StoRIES, the Helmholtz MCDA (Multi-Criteria Decision Analysis) Tool (HELDA), developed by KIT is a structured, science-based decision-support framework to evaluate complex technological choices, policies, or system options where often conflicting criteria must be considered simultaneously. One of its core strength lies in combining quantitative assessment with qualitative judgment, while also embedding stakeholder participation into the process. This makes it particularly well-suited for applications in sustainability, energy transition, and infrastructure planning. The software is freely available after registration [93]. A screenshot of the interface is provided in Figure 8.

Figure 8: Screenshot of the HELDA tool [93]



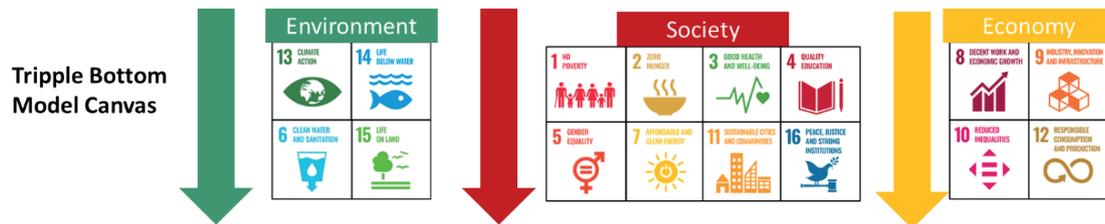
The Business Sustainability Canvas Template

A special recommendation from StoRIES, to translate sustainability into *business planning* and implementation, is the use of a BSC, especially in the triple-layer version. This tool extends the classic BSC with two additional layers for environmental and social issues, allowing a holistic business model for a technology or project to be outlined. This tool guides users in assessing hybrid energy projects from multiple stakeholder perspectives, including manufacturers, system integrators, and end-users. An overview of the structure is provided in Figure 9. The **triple-layer business model canvas** consists of:

- **Economic layer:** Corresponds to the traditional canvas (customer segments, value propositions, channels, customer relationships, revenue streams, key resources, activities, partners and cost structure). This is where the *business logic* and economic benefits of the HES project are typically recorded – e.g. which customer problem is solved by the HES (value proposition: e.g. “reduces energy costs and CO₂ emissions for industrial customer X”), how money is earned or saved, etc.
- **Environmental layer:** This canvas layer transfers the findings of the life cycle assessment and environmental assessment into the business model. Typical fields here include, for example: “Life cycle materials” (which materials/raw materials go into the product – and their origin, certification, etc.),

"Manufacturing and supply chain (production footprint)", "Use & energy" (environmental impacts during the use phase, e.g. power consumption, emission savings at the customer), "end-of-life" (recycling strategy: recycling, reuse), and "environmental cost structure" (external costs, CO₂ price, savings). The aim is to firmly integrate ecological sustainability aspects into business planning. For example, one would note here that HESS reuses *secondary batteries from electric vehicles* – which reduces raw material costs and avoids waste. Or that HES avoids a certain amount of tonnes of CO₂ per year at the customer's site, which could be monetarily relevant in the future (CO₂ pricing).

Figure 9: Structure of the business canvas template, starting from a classic template



- **Social layer:** This layer highlights the social and societal values of the business model. Elements may include: “*Social value creation/promise*” (e.g. “*Enables local citizen participation in storage projects*” or “*Increases grid stability and thus security of supply for communities*”), “*Employees & skills*” (which jobs and qualifications are created), “*community & society*” (local acceptance, participation, social benefits), “*governance & partnerships*” (how fairness, transparency and compliance are ensured), etc. *Risks* can also be addressed (violation of labour rights in the supply chain; governance measures). The results of social impact assessments are incorporated here. For example, if the social LCA has shown that there are risks in the cobalt supply chain, the canvas would note that the business model provides for a supplier code of conduct or recycling to reduce primary cobalt.

Filling in all three layers creates a holistic picture of the planned HES business or project. StoRIES has specially adapted such a canvas by assigning the relevant sustainability KPIs to the canvas fields. For example, ESG metrics are placed along the value chain: from material suppliers to manufacturers to system integrators, sustainability KPIs are anchored so that the business model goes beyond purely economic considerations. For decision-makers and developers, the triple-layer canvas offers the following advantages:

- **Structured integration:** It forces sustainability to be viewed not in isolation, but directly interwoven with the business strategy. This makes it clear where sustainability issues represent opportunities or risks in the business model (e.g. recycling as an additional source of income, or material shortages as a cost risk).
- **Communication:** It serves as a visual communication tool for stakeholders (investors, partners, authorities). A canvas can be presented in an easily understandable way. In particular, the presentation of environmental and social benefits at a glance increases acceptance among funding providers and the public.
- **Innovation:** Thinking about the three layers in parallel can give rise to new ideas, such as service models (pay-per-use storage leasing) that are economically viable and at the same time ecologically sensible (shared economy approach, more intensive use per unit) and socially beneficial (local participation).
- **Checks & balances:** It helps to identify trade-offs in the business model. For example, a model could be economically profitable but cause environmental problems – in the canvas, the environmental layer would have negative entries, signaling that the model is not sustainable and needs to be adapted.

In practice, after carrying out the quantitative sustainability analyses, the project team should fill in the triple-layer canvas step by step: first economically (business case), then add the ecological findings (where do emissions/costs occur, how can the model respond to this), then add the social aspects (stakeholder map, governance). Such a sustainability canvas can, for example, be part of a funding application or business plan to demonstrate that the HES project has been thoroughly thought through.

TAKE AWAYS FOR HESS SUSTAINABILITY ASSESSMENT



To ensure the sustainable deployment of HESS, it is essential to apply not only rigorous technical evaluation methods but also participatory approaches that incorporate diverse stakeholder perspectives. The StoRIES project has demonstrated a successful, scalable model that integrates both quantitative and qualitative tools for evaluating emerging energy technologies across technical, environmental, economic, and social dimensions. The following best practices are recommended for future sustainability assessment processes and participatory decision-making frameworks.

Use Realistic, Context-Specific Use Cases: Sustainability assessments are most effective when grounded in real-world applications. The StoRIES workshops showed that tailoring evaluations to clearly defined use cases such as emergency hospital backup or seasonal district storage helps stakeholders engage meaningfully with the technology and its implications. Use cases anchor abstract KPIs in tangible settings, which improves both the relevance and clarity of assessment results.

Apply a Multi-Layered Assessment Framework: A robust sustainability analysis must draw on multiple methodologies, including LCA, s-LCA, LCC, and MCDA. The integration of these tools supports a comprehensive understanding of the impacts, trade-offs, and potential benefits of hybrid storage systems. MCDA, in particular, enables structured prioritisation of criteria, supporting decision-making where multiple values and interests are at play.

Integrate Stakeholder Participation Early and Continuously: Effective stakeholder integration must begin in the early design phase and continue through technology evaluation and scenario development. Using participatory formats, such as sustainability business model canvases, card-based MCDA exercises, and facilitated workshops, enables stakeholders to express values, negotiate trade-offs, and co-create more acceptable and robust outcomes. StoRIES findings highlight that later-stage group discussions significantly expanded the prioritization of indicators like circularity, energy security, and public trust, which were underrepresented in initial individual ratings.

Balance Expert Judgment with Inclusive Dialogue: Initial technical preferences often reflect institutional or disciplinary biases. Facilitated group processes help stakeholders reflect on broader system-level needs and revise their positions based on peer input. Combining individual scoring (e.g., online surveys) with group-based deliberation (e.g., deck-of-cards ranking) enhances both inclusivity and legitimacy of outcomes.

Use Structured Templates and Visual Tools: Tools such as the BSC and visual MCDA plots (e.g., spider diagrams) are essential for aligning discussions, identifying knowledge gaps, and maintaining focus. These instruments make abstract assessments more accessible, especially for non-technical participants, and help bridge the gap between sustainability theory and business or policy practice.

Track Emerging Criteria and Contextual Indicators: The participatory format used in the StoRIES workshop revealed additional KPIs that were not part of the initial framework but emerged through discussion, such as reliability, resilience enhancement, investment feasibility, energy security, and social welfare. Future assessments should remain flexible and allow space for emerging concerns to be incorporated dynamically.

Facilitate Transparent Documentation and Open Sharing: Documenting the process from initial voting to final prioritization ensures transparency and reproducibility. Creating shared, open-access databases of sustainability KPIs, methodological guidelines, and case study results can foster harmonization and cross-project learning across Europe's energy transition ecosystem.

HESS MCDA USE CASE



The following section provides an overview of how to further extend the qualitative results of the workshop towards a more founded format. This phase transforms participatory insights into actionable, evidence-based sustainability evaluations bridging the gap between stakeholder expectations and rigorous system-level validation.

Please note

The Use case is intended to show the capabilities of the approach developed in STORIES and does not substitute a in depth assessment. The data used is based on existing models and approximations which is acknowledged via the uncertainty assessment. However, a study using primary data is recommended for the evaluation of HESS.

Goal and Scope

The use case assumes a **grid-connected microgrid** that can island during outages; thus the HES is used both for daily energy management (storing surplus solar energy for evening use, shaving peak demand) and backup power during grid interruptions. By design, the combination of storage technologies should handle a range of needs: energy shifting (hours of storage from batteries and flow cells) and high-power surges (fast response from supercapacitors).

A real-world example is a residential microgrid where a battery system (on the order of 1,2 MW / 1 MWh) was installed to replace conventional grid supply, successfully improving renewable energy reliability for multiple households. The reference case is linked to the system layout for Heigl et al. [94]. The hybrid storage consists of a 900kW/0.9kWh Super Capacitor part and 300 kW and 1,400 kWh storage capacity. It is helpful to benchmark HESS concepts against established and emerging reference technologies. This helps to contextualise performance, identify relative advantages of HESS (if any), and validate stakeholder-driven priorities using standardised sustainability assessment methods. Here a sodium-Ion-Prussian blue Analogue type (SiB PbA), Lithium Iron Phosphate (LFP) and a Vanadium Redox Flow battery are selected as reference technologies. It is assumed that all named batteries have to be able to provide the peak power of 1,200 kW, and provide a maximum of 4.6 hours of energy following the layout of the hybrid storage use case. The project duration is set to 20 years, with about 1.5 full cycles per day operation mode. Table 3 provides an overview of the named technologies considered for the use case.

Table 3: Description of the considered alternatives

Technology	Description	Specification
LFP	Lithium-ion chemistry using LiFePO ₄ cathodes and Graphite; very safe and long-life with good power capability, but lower energy density than NMC. Common in EVs and stationary storage.	1.2 MW and 1.401 MWh with Inverter system
SiB (PbA)	Sodium-ion cells with Prussian-blue-analogue cathodes and hard carbon; uses abundant sodium, moderate energy density, good low-temperature/fast-charge behavior, and attractive cost for grid/storage uses.	
Vanadium Redox Flow	Aqueous flow battery with vanadium electrolytes in two tanks; power scales with cell stack, energy with tank size. Long cycle life, deep discharge, high safety; lower energy density.	
Hybrid Redox Flow Battery with supercapacitor.	VRFB paired with a supercapacitor bank via DC-DC converters: supercaps deliver/absorb fast transients and peaks, while the VRFB provides sustained energy, improving response and reducing stack stress.	<ul style="list-style-type: none"> ▪ 1.2 MW Inverter ▪ SuperCaps 900 kW, 0.9 kWh ▪ VRFB: 300 kW; 1400 kWh

The system boundary encompasses the entire lifecycle of each storage technology. This includes the production phase - covering mining and processing of raw materials, component manufacturing, and assembly of batteries and supercapacitors - as well as the transport and installation of the storage system on-site. The operational phase is also included, which involves charging from PV sources, discharging to supply local energy demands, and managing auxiliary energy requirements such as cooling, pumps, and routine maintenance. While end-of-life (EoL) processes, such as recycling, material recovery, or disposal of batteries and electrolytes, are not explicitly assessed in this analysis, their potential impacts are acknowledged within the broader set of KPIs.

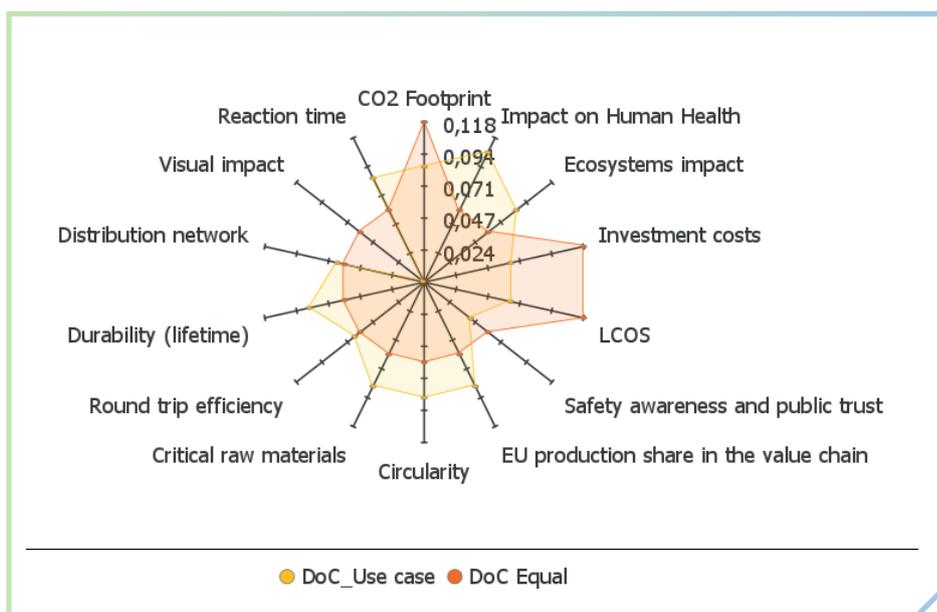
The microgrid's renewable generation and power conversion equipment (inverters, control systems) are considered in terms of their influence on storage usage (e.g. charging patterns) but their impacts are not detailed in this assessment to maintain focus on the HESS itself. It is assumed that the microgrid remains mostly grid-connected for stability, exporting or importing small amounts of energy as needed; however, during the operation, the storage is actively managing the energy balance (either storing excess renewable energy or supplying deficit). During those hours, the microgrid may operate islanded or in parallel with the grid, but in either case the storage is important for reliability. Thus, the boundary includes any interaction losses (e.g. inverter losses) associated with charging/discharging the HESS, since those affect the efficiency and required generation.

Sustainability assessment example via MCDA

The MCDA based evaluation has been carried out for the four named technologies using HELDA. For this the before shown weights from the "Deck of Cards" (DoC) exercise are combined with the performance of the identified indicators. The DoC format encourages groups of stakeholders to collectively assign relative importance to the various indicators, reflecting the insights gained during earlier discussions, here the 3rd workshop. Here the DoC results from WG II are used and changed slightly to account for distinct application case that favours HESS. This was done by adding a KPI on reaction time, which is an important KPI to assure power quality control and to guarantee fast power back up without delays. In addition, the KPI Distribution Network was ranked one level higher in the DoC, with the goal to better exploit the current grid infrastructure of the residential use case, avoiding additional investments in e.g. grid reinforcement or additional back up devices. For details please refer to the [ANNEX II](#).

The used aggregation method is PROMETHEE II, which produces a complete ranking of alternatives by computing a *net outranking flow* for each alternative (positive flow minus negative flow). It requires defining preference functions and weights for criteria, then comparing each pair of alternatives across all criteria. Preference functions are mathematical tools that transform the difference in performance between two alternatives on a criterion into a preference degree ranging from 0 (no preference) to 1 (strong preference). They allow decision-makers to model how sensitive comparisons are to performance gaps, using different shapes (e.g., usual, U-shape, V-shape, linear Gaussian) depending on the criterion's nature. Respective preference (p) and indifference parameters (q) need to be defined by the analyst together with decision-makers. Other methods available in HELDA are e.g. ELECTRE III; or compensating methods as VIKOR or TOPSIS [93].

Figure 10: Adopted weights set from WG2, with reaction time as new KPI (Graphs taken from HELDA [93])



Performance matrix for storage evaluation

A performance matrix is required to carry out a ranking and to understand the impact of the most critical KPIs to the overall performance of the analysed ES. Here the KPIs are measured in a semi-quantitative way. An overview of the filled-out performance matrix is provided in Table 4. Within the table four energy storage options Vanadium Redox Flow Battery (VRFB), Hybrid VRFB+SuperCap, Lithium Iron Phosphate (LFP), and Sodium Ion Battery (SiB PbA) were compared across twelve sustainability KPIs using scales and own calculations. Each KPI has a defined preference direction (maximize or minimize), ensuring that higher scores consistently indicate stronger sustainability or performance outcomes. The colour codes for the point scales shall ease the understanding of the attributed values.

Table 4: Performance Matrix for the MCDA-evaluation of the considered ES and KPIs.
 Note, the KPI reaction time has been added for reasons of context.

Sustainability KPI	Preference direction	Unit	Vanadium Redox Flow Battery	Hybrid Vanadium Redox Flow Battery+ Supercaps	Lithium Iron Phosphate	Sodium Ion Battery Prussian Blue
Safety perception and public trust	maximize	scale 1-5	5	5	3.5	4
Visual impact	minimize	Scale 1-5	3	3	2	2
EU production share in the value chain	maximize	Scale 1-5	2	3	1.5	2
Circularity	maximize	Scale 1-5	5	4.5	2	2
Critical raw materials	minimize	Scale 1-5	4	4	3.5	2
Distribution network	maximize	Scale 1-5	3	5	4	4
Reaction Time	Maximize	Scale 1-5	3	5	4	4
Efficiency	maximize	%	75	74	92	92
Durability	maximize	Cycles	15000	18000	6000	4000
CO ₂ footprint	minimize	kg CO ₂ eq / kWh	0.05	0.049	0.021	0.035
CAPEX	minimize	€/kW	3540	2522	1424	1425
LCOS	minimize	€/kWh	46	33.8	18.8	19.5

The LCOS, CAPEX and CO₂ performance was calculated using own models used in previous publications [39, 43, 47, 67, 95]. The LCOS calculus is based on an annuity method approach, using a depreciation rate of 7%. For the hybrid storage system information was derived from [94], based on the Hyflow project. However, the hybrid storage system had to be approximated using a updated model of [95] due missing information in the LCI. The values for super capacitors have been approximated by existing values provided by [96] and internal discussion. The model for LCOS and CO₂ footprint considers potential cell exchanges and considers potential technological development (e.g. +% of cycle lifetime or efficiency after n years). For the LCOS decreasing cost over time is accounted (learning curves) for each technology. Additionally, depreciable values are credited to each single technology (e.g. LCOS are reduced by the remaining value if a technology is exchange at year 18). CAPEX is based on cell and BOP cost, which in turn depend on the size taking into account scaling effects, for details see [67]. It should be noted that the VRFB performance is highly dependent on the Energy to Power ratio. Here the VRFB results are quite high due to a very unfavourable energy to power ratio of 1200 kW to 1400 kWh, which results in high cost and emissions related to the reaction stack which is modelled by a bottom up approach adopted from [97]. The hybrid storage technology system was modelled with a more favourable E/P ration adding cost for the Supercapacitors based on [98]. Table 5 in ANNEX I shows that SIB (PBA) benefits from low CRM, decent efficiency/LCOS and CO₂. The Hybrid VRFB+SC lifts VRFB on transients/durability while mitigating efficiency. VRFB is strong on safety, circularity, durability; but limited by CAPEX/LCOS/CO₂. It is worth mentioning that the attribution of values and the calculation of LCOS and other KPIs depends on multiple aspects which have not been considered here, as e.g. the influence of different

HESS management systems [99]. In general, the assessment conducted serves primarily to display the potential impact of different applications and preference contexts.

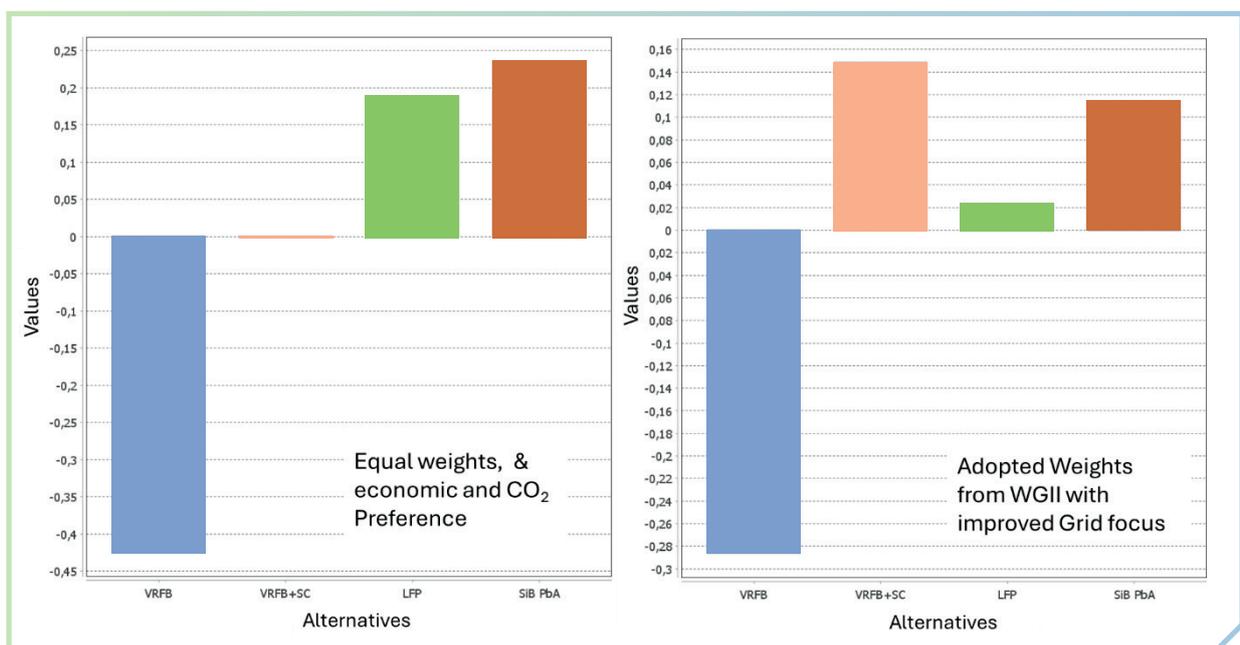
Table 6 in ANNEX I outlines these indicators and qualitatively rated expectations for each of the HESS technologies (LFP, Na-ion/PbA, VRFB, Hybrid) in the residential/commercial microgrid context. This matrix approach ensures that all key aspects are considered side by side. The values for the triangular evaluation for the point scales are provided in the annex. There is a high uncertainty related to the performance data, which is considered in frame of the used case. The uncertainty of calculated values for LCOS, CAPEX and GWP are modelled following the recommendation of [139], [140] on base of a pedigree matrix (see annex). Uncertainties for all point scale evaluations are converted into the triangle functions to account for the semiquantitative nature of the evaluation. Here, minimum, maximum, and most likely values that reflect expert opinion or limited data was assigned, enabling a more robust analysis of mostly subjective criteria. The distribution functions are accordingly selected in the performance matrix of HELDA.

Results

Figure 11 illustrates how weighting strategies and criteria preferences influence the ranking of storage alternatives using the weights shown Figure 11. The left bar charts show that under equal weighting with a focus on economic (LCOS, CAPEX) and CO₂ aspects, SiB PbA scores highest, followed by LFP, while VRFB+SC remains neutral and VRFB performs worst. However, when weights are adapted with a stronger grid focus (adopted WG II perspective), the picture changes: VRFB+SC ranks first, outperforming both SiB PbA and LFP, confirming its strength in durability, circularity, and grid services.

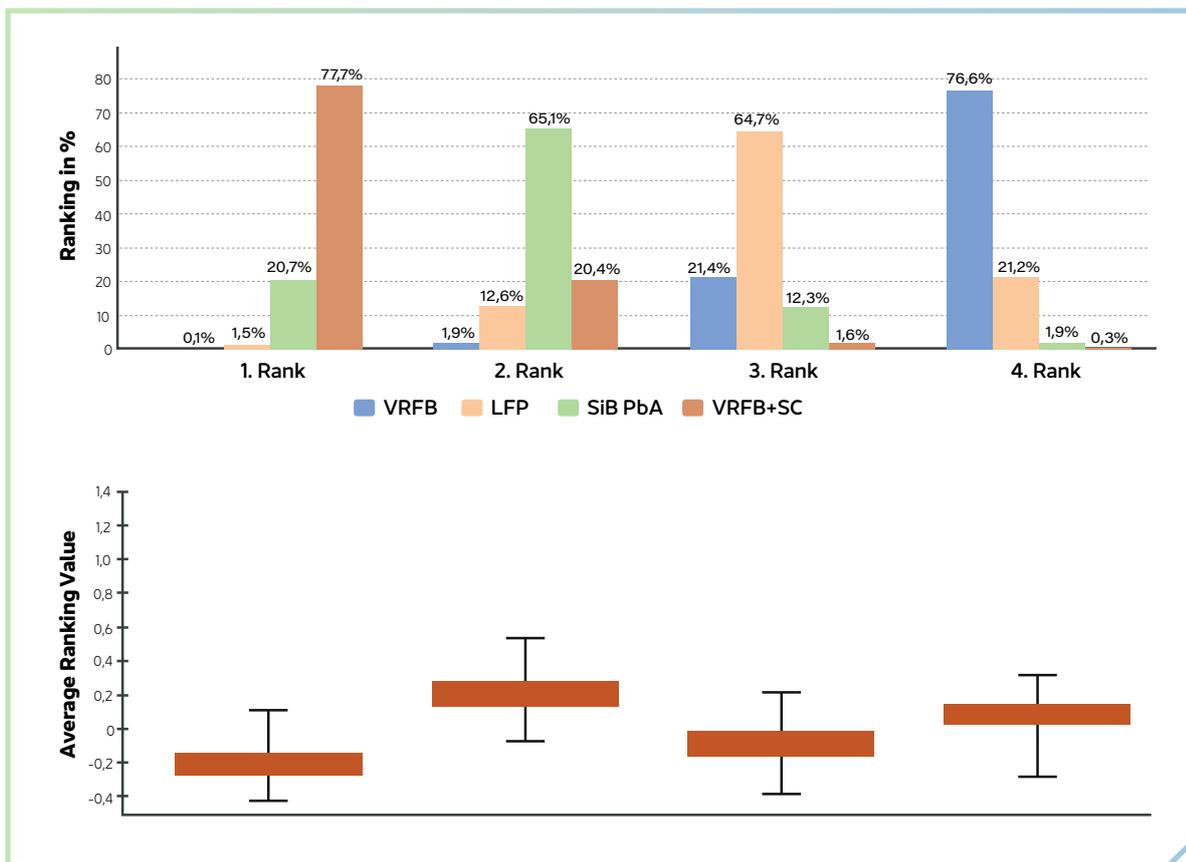
While an equal weighting with economic and CO₂ focus emphasises a balanced distribution, the use-case weighting shifts priority towards CO₂ footprint, circularity, and durability, reflecting the broader perspective. This highlights that different stakeholder preferences and application contexts can significantly affect the outcome. The left, WG II based weights are used for the following results, where VRFB+SC consistently emerges as the most robust long-term solution if the priorities are set towards short term grid stability and mid-term storage.

Figure 11: Comparison of the results for equal weighted KPIs with GWP, LCOS and CAPEX focus vs. adopted Weights of WGII (Graphs taken from HELDA [93])



A Monte Carlo simulation (n=1000) is carried out in HELDA to assess uncertainties of input data, i.e. uncertainty of performance data. Results show that the rankings are robust based on the adopted weights of WG II, with VRFB+SC ranking first, followed by SiB. LFP is certainly ranked third, whilst VRFB is ranked last. The Boxplots show that there is a high variation in the average ranking values due to the high uncertainty related to the evaluated KPIs, in particular LCOS, CAPEX and CO₂ eq./kWh.

Figure 12: Results of the MCS based on the adopted weights from WG II (Graphs taken from HELDA [93])



The multi-criteria evaluation of the four storage alternatives and the adopted weights from WG II shows VRFB+SuperCap as the strongest option, with a higher score than SiB PbA, while LFP and VRFB rank significantly lower. Fourteen sustainability criteria were considered, ranging from environmental and social impacts to technical performance and costs. The analysis shows that no single criterion dominates the outcome; instead, multiple factors such as circularity, reaction time, durability, and critical raw materials together shape the ranking. Cost-related indicators like CAPEX, LCOS, and efficiency favour SiB PbA and LFP, yet these advantages are outweighed by weaknesses in lifetime, circularity, and EU production share. VRFB+SC, despite higher costs, benefits from superior durability, strong circularity, and very fast reaction times, resulting in the most balanced performance. Sensitivity testing confirms the robustness of this result, as even large changes in weighting do not alter the top ranking. Correlation analysis further reveals trade-offs, particularly between efficiency and broader sustainability indicators. Overall, the study underscores that while VRFB+SC currently represents the most sustainable hybrid solution, no single technology can be universally recommended, and context-specific priorities will remain decisive in guiding future applications.

Discussion

No specific technology is recommended unconditionally; rather, the study underscores the importance of transparent weighting, careful interpretation of correlated criteria, and context-specific application when choosing sustainable hybrid storage solutions

Each workshop group developed tailored business models and prioritised key sustainability criteria for specific HESS use cases. However, to transition from qualitative insights to quantified evaluations, HESS solutions must be compared with relevant technologies currently used or proposed for the same applications. This ensures that:

- Sustainability assessments are grounded in realistic performance expectations.
- Policy and investment decisions are based on comparative impact and viability.
- Hybrid solutions are evaluated not in isolation but relative to current market options.

Benchmark technologies must be selected based on their maturity, functional equivalence, deployment scale, and relevance to the specific application contexts explored during the workshop (emergency backup, microgrids, seasonal storage).

CONCLUSIONS AND NEXT STEPS

8

The transition to a climate-neutral, resilient, and affordable energy system in Europe requires more than just technological advancement. It demands a structured, transparent, and inclusive approach to assess and guide innovation. HESS offer a unique opportunity to address technical and sustainability challenges by combining the strengths of multiple storage technologies. However, their complexity also necessitates robust frameworks for evaluation, stakeholder engagement, and long-term deployment strategies.

The work conducted in the StoRIES project, including the development and application of sustainability KPIs, the use of BSC, and the implementation of participatory MCDA tools, provides a comprehensive blueprint for how such evaluations can be carried out in practice. By combining technical metrics with environmental, social, and economic criteria and by incorporating diverse stakeholder perspectives throughout the three workshop processes, the project has shown that informed, balanced, and broadly accepted decisions are achievable.

The key findings underline the importance of co-creation in technology development: stakeholder priorities evolved significantly from initial assumptions to refined group consensus, particularly in relation to social value, circularity, and resilience. This evolution demonstrates the strength of participatory methods and their role in enhancing both legitimacy and system alignment in energy planning.

To further accelerate the sustainable deployment of hybrid energy storage systems, the following actions are recommended:

1. **Institutionalise Sustainability KPIs in Policy and Procurement:** Ensure that standardised, multi-dimensional KPIs are embedded into public funding calls, infrastructure planning, and regulatory assessments at both EU and national levels.
2. **Support Scalable Demonstration Projects:** Encourage pilot deployments of HESS technologies using the BSC as a guiding framework for identifying value propositions, stakeholder roles, and potential barriers.
3. **Expand Stakeholder Engagement Platforms:** Scale up participatory processes using tools like the HELDA and DoC prioritisation to include more diverse actors such as citizens, SMEs, and regional authorities.
4. **Develop Shared Open-Access Resources:** Build and maintain an open library of KPIs, case studies, business model templates, and methodological guides to support wider application and capacity building.
5. **Encourage Cross-Sectoral Research and Training:** Promote interdisciplinary academic-industry partnerships to deepen understanding of hybrid storage systems, including technical integration, social acceptance, and life-cycle impacts.

- 6. Monitor and Update Assessment Frameworks:** As society and technology priorities advance, the criteria used for assessment must also adapt and evolve. Future updates to the framework should be informed by real-world deployment data, regulatory shifts, and continued stakeholder dialogue.

Recommendation for different stakeholder groups

The activities conducted within the workshops allow us to derive recommendations for different stakeholder groups, which can of course be deepened in future projects. In principle, three groups can be addressed, policy makers, industrial actors and academia using the insights of the third workshop. These recommendations are also reflected in the StoRIES SRIA and the Roadmap.

Policy

HESS represent a key enabling technology for Europe's transition to a climate-neutral energy system. Given their capacity to combine the strengths of different storage technologies, such as fast response with high energy density, they are uniquely positioned to deliver flexibility, resilience, and sustainability across applications ranging from emergency backup to seasonal storage. However, the implementation of HESS still faces systemic challenges that call for targeted policy intervention.

Policymakers at the EU and national levels should prioritize regulatory clarity and market frameworks that recognise and incentivise hybrid solutions. This includes updating grid codes and permitting rules to reflect the value of systems that operate across multiple services (e.g., energy shifting, frequency regulation, and backup power). Hybrid systems should also be integrated into the broader EU Taxonomy and Renewable Energy Directive frameworks to ensure they are not disadvantaged compared to single-technology solutions.

To reduce adoption barriers, policies should support financial de-risking mechanisms such as subsidies, tax incentives, or innovation funds for early-stage hybrid storage pilots. These financial tools should reward systems not only for cost-efficiency but also for measurable sustainability outcomes across technical, environmental, and social KPIs. Furthermore, there is a need to streamline access to public procurement pathways, particularly for applications like critical infrastructure, where reliability and public safety are paramount.

Strategically, the EU should foster standardisation and shared data frameworks to enable lifecycle assessments, circularity tracking, and comparability across hybrid systems. Finally, facilitating structured stakeholder engagement through tools like MCDA should be embedded in policy development and infrastructure planning, ensuring that technology evaluations are both inclusive and transparent.

Industry

For companies active in energy storage technology and systems integration, the StoRIES outcomes point to several strategic opportunities. First, there is a clear need to align product development with evolving sustainability KPIs. This means designing hybrid systems that not only optimise performance (e.g., LCOS, cycle life) but also address broader social and environmental goals such as circularity, health impact, and CO₂ reduction. Manufacturers and integrators should prepare to articulate the value proposition of hybrid systems within diverse use cases, from hospitals and residential microgrids to seasonal district storage. The BSC used in the workshops offers a practical template for mapping customer needs, technical benefits, and revenue models in a way that is aligned with both user expectations and regulatory priorities. Engaging early with municipalities, utilities, and regulators through co-creation

workshops or pilot programs can also accelerate market entry and build public trust. Emphasis should be placed on modularity, safety, low-maintenance design, and integration readiness with existing infrastructure. Additionally, building transparent end-of-life and recycling strategies into business models will be essential as circular economy policies tighten. Finally, industry players are encouraged to engage with evolving EU sustainability regulations not only as compliance challenges but as innovative drivers. Participating in standard-setting initiatives, contributing to open KPI databases, and supporting integrated assessments (e.g., via LCA or s-LCA) will position firms competitively in a future-proof market.

Academia

For researchers and academic institutions, StoRIES highlights the critical role of science-based assessment frameworks and participatory methodologies in guiding sustainable innovation. There is a strong demand for continued development of multi-method sustainability assessments, integrating tools such as MCDA, LCA, and social impact metrics to evaluate complex hybrid systems holistically. Academia should work closely with stakeholders to co-develop use-case-driven research, providing data, models, and evaluation methods that reflect real-world complexity. Research should also focus on closing knowledge gaps in areas such as resource criticality, heat utilisation efficiency, and long-term system integration impacts. Educational institutions can play a transformative role by training the next generation of professionals in systems thinking, participatory evaluation, and cross-sectoral sustainability planning. Embedding tools like the BSC and MCDA into curricula can help students and researchers become fluent in bridging technical and societal considerations. Lastly, academic partners should continue to support open science and data sharing, contributing to the creation of common assessment platforms and indicator libraries that serve both public and private sector needs.

In conclusion, the path forward for HESS depends on coordinated action across policy, industry, and research. With targeted policies, sustainability-driven innovation, and collaborative evaluation, HESS can become a cornerstone of Europe's flexible, decarbonised, and resilient energy future as described in the StoRIES SRIA [7] and Roadmap [33].

Final remarks

By embedding these actions in ongoing policy and innovation ecosystems, Europe can not only unlock the full potential of hybrid energy storage, but also ensure that this transformation is sustainable, inclusive, and aligned with long-term societal goals.

ANNEXES



ANNEX I

Table 5: Used rationales for attributing scores to the different technologies (Semi-qualitative)

Sustainability KPI	Preference direction	Evaluation Rationale for 5 point scale
Safety perception and public trust	maximize	5 = non-flammable electrolyte & benign failure modes; 3 = flammable electrolyte with proven safety enhancements; 1 = high TR risk
Visual impact	minimize	5 = >2x site area vs baseline container/MWh; 3 = ±25%; 1 = ≤-25%.
EU production share in the value chain	maximize	Mining & Materials+Manufacturing+System Integration 5, Manufacturing+System Integration =3, Only System Integration = 1
Circularity	maximize	≥90% mass recovery or direct reuse of active materials; 3 = industrial recycling exists but open-loop; 1 = no viable route
Critical raw materials	minimize	5 = relies on ≥2 CRMs by mass/critical function; 3 = 1 CRM with substitutes; 1 = no CRMs (per EU-2023 list)
Distribution network	maximize	5 = No grid reinforcement needed; technology inherently stabilizes distribution networks. 4 = Minimal adjustments required. 3 = Moderate reinforcement required. 2 = Significant reinforcement required. 1 = Strongly dependent on grid reinforcement.
Reaction Time	maximize	5: < 10 ms to rated power; very high pulse power (supercap). 4: 10–50 ms typical; high-power cells (≈ 1–2 C+) and PQ-capable PCS.3: 50–200 ms typical; adequate for primary frequency/PQ2: 200–500 ms.1: > 500 ms. [135]

Table 6: Score attribution rational

Sustainability KPI	Preference Direction	Score	VRFB	VRFB& SuperCap	LFP	SIB (PbA)	Note
Safety perception & public trust	Max	1–5	5 – Aqueous, non-flammable electrolyte; benign failure modes	5 – As VRFB plus added PQ control from SCs	4 – Low TR risk with BMS; residual flammability concerns	4 – Non-Li chem.; low TR; fewer incidents known	Derived from material shares and literature
Visual impact	Min	1–5	3 –tank footprint; containerized	3 – Similar to VRFB; added PCS/SC rack	2 – Compact containers; smaller site area/MWh	2 – Compact modular racks; low profile	Derived qualitatively [100]

EU production share in value chain	Max	1-5	2 – Partial EU stack/BOP; electrolyte supply mixed	3 – More EU system integration for hybrid PCS/ controls and supercapacitor prod.	1.5- Cell supply largely non-EU; EU integration	2 – Early EU footprint; mixed supply chains	Derived from material shares and literature [136] [137]
Circularity	Max	1-5	5 – ≥90% mass recovery; electrolyte reuse; mature routes	4 – Same routes as VRFB; more diverse with SuperCapacitors, no closed loop recycling	2 – Open-loop/limited closed-loop today, current collectors, casing	2 – Recycling routes emerging; low recovery today, current collectors, casing	Derived from material shares and literature
Critical raw materials (minimise)	Min	1-5	4 – Vanadium recyclable; but high V2O5 impact	4 – As VRFB recyclable but high V2O5 impact; SC uses standard carbons/Al/Ni	4 – Limited CRM content in LFP (phosphate, Lithium, Graphite)	2 – Prussian blue precursors & Na supply okay; balance metals/ components raise exposure	See Table XX, compo in Annex sition of alternatives and [43]
Distribution network	Max	1-5	3 – Good for shifting; slower PQ response may need local tuning	5 – No reinforcement; fast Q/peaking/ congestion relief	4 – Generally, grid-friendly; minor settings/ controls	4 – Grid-friendly; minor adjustments only	[99]
Reaction time	Max	1-5	3 – 200–500 ms typical	5 – <10–50 ms with supercap	4 – 50–200 ms with PCS	4 – 50–200 ms with PCS	[135], [138]

Table 7: Pedigree matrix evaluation for Data quality [139], [140]

	1 (Best)	2	3	4	5 (Worst)
Reliability of source	Verified measurements	Verified but partly assumption-based / or nonverified from measurements	Nonverified, partly based on assumptions	Qualified estimate (e.g., industrial expert)	Nonqualified estimate or unknown origin
Completeness	Representative data from many sites over adequate time	Representative data from fewer sites, adequate time	Representative data from adequate sites but shorter time	Representative but from fewer sites & shorter time, or incomplete from adequate sites	Representativeness unknown or incomplete from fewer/shorter samples
Temporal differences	<0.5 years from study year	<2 years difference	<4 years difference	<8 years difference	Age unknown or ≥8 years difference
Geographical differences	Same area, same currency	Larger region incl. study area, same currency	Similar cost conditions, same or similar currency	Slightly similar cost conditions, different currency	Unknown area or very different cost conditions
Further techno-logical differences	Data from enterprises/ processes/ materials under study	Same processes/ materials from different enterprises, similar accounting	Same processes/ materials but different technology and/or different accounting	Related processes/ materials, same technology	Related processes/ materials, different technology

Table 8: Uncertainty evaluation of data for used KPIs

KPI	Technology	Score: Relial	Score: (Score: (Score: Te	Sum sigma ²	GSD
CO2 footprint	Vanadium Redox Flow Battery	2	2	3	2	2	0.227707582 1.611535025
CO2 footprint	Hybrid Vanadium Redox Flow Battery	3	3	3	2	4	0.777702764 2.415423355
CO2 footprint	Lithium Iron Phosphate	1	2	1	2	2	0.032187497 1.196509708
CO2 footprint	Sodium Ion Battery Prussian Blue analogues	2	3	2	2	2	0.220161816 1.598737157
CAPEX	Vanadium Redox Flow Battery	2	2	3	2	2	0.234411132 1.622811655
CAPEX	Hybrid Vanadium Redox Flow Battery	3	4	3	2	3	0.503204209 2.032707973
CAPEX	Lithium Iron Phosphate	1	1	1	2	2	0.038017324 1.215287066
CAPEX	Sodium Ion Battery Prussian Blue analogues	3	2	1	2	2	0.26569004 1.674393981
LCOS	Vanadium Redox Flow Battery	2	2	3	2	2	0.234411132 1.622811655
LCOS	Hybrid Vanadium Redox Flow Battery	3	4	3	2	3	0.503204209 2.032707973
LCOS	Lithium Iron Phosphate	1	1	1	2	2	0.038017324 1.215287066
LCOS	Sodium Ion Battery Prussian Blue analogues	2	3	1	2	2	0.225991644 1.608634663

Table 9: Rational for Distribution grid

Score	Evaluation Rationale Distribution Grid
5	No reinforcement needed; technology inherently stabilizes the grid. Provides ancillary services (frequency control, peak shaving, congestion relief) and connects flexibly at multiple voltage levels. Reinforces distribution stability without local upgrades.
4	Minimal adjustments required (e.g. control software, minor protection systems). Largely compatible with the grid but may show limitations under extreme load or transient events.
3	Moderate reinforcement required (e.g. transformer/line upgrades). Can integrate, but grid stress possible during peak or variable renewable input. Contribution to stability is partial.
2	Significant reinforcement required. Technology imposes stress on voltage/frequency balance unless major adaptations are made.
1	Strongly dependent on grid reinforcement. Cannot be deployed without major restructuring; high risk of destabilizing distribution networks.

Table 10: Reasoning for Recyclability

Technologies	VRFB	VRFB+SuperCap	LFP	SIB
Material composition	Electrolyte Vanadium Pentoxide: 88.31% (Theoretically: <90%) Steel: 0.73% (31%), Copper: 0.55% (30%), Al: 3.77% (21%), Rubber:0.74% (1%), Others: 6 (N/A), RFB electrolyte is recoverable and re-usable (>80–90% of vanadium can be recovered; electrolyte can be reused directly) [95]	Electrolyte: 88.31% (Theoretically: <90%) [Ref] Steel: 0.73% (31%), Copper: 0.55% (30%), Al: 3.77% (21%), Rubber:0.74% (1%), Others: 6 (N/A) Supercapacitor (gh-surface-area activated carbon coated on aluminum foil current collectors, Nickel and steel.) RFB electrolyte is recoverable and re-usable (>80–90% of vanadium can be recovered; electrolyte can be reused directly)[94, 95]	Lithium:11% (0%) Iron: 9.2% (31%) Aluminium: 6% (21%) Copper: 17% (30%) Graphite: 15% (3%) Phosphate: 15.6% (17%) Rest: 36% recycling routes exist but are not yet widely closed-loop for all materials [45], [141]	Hard carbon 21%, Aluminium 13%, Prussian Blue 32.4%, NaPF6 26.7%, Recycling routes do not exist but are not yet widely closed-loop for all materials [47]

Table 11: Reasoning for raw Material Criticality based on [142] and [41]

VRFB	VRFB&SuperCap	LFP	SiB
Relies on vanadium (EU-listed CRM) as the core active material; exposure concentrated in one CRM → high reliance. Electrolyte Vanadium Pentoxide: 88.31% (Theoretically: <90%)	Relies on vanadium (EU-listed CRM) as the core active material; exposure concentrated in one CRM → high reliance. Electrolyte Vanadium Pentoxide: 88.31% (Theoretically: <90%), addition of additional material demand vis supercaps (e.g. current collectors)	Uses lithium (CRM), natural graphite (CRM), and phosphate rock (CRM precursor to cathode). That's ≥2 CRMs embedded in the value chain.[43]	No CRM

Table 12: Values for distribution functions, partially derived from Pedigree matrix.

Criteria	Alternative	Distribution	Criteria (continued)	Alternative	Distribution
CO ₂ Footprint	VRFB	Triangular Distribution:	Critical raw materials	VRFB	Triangular Distribution:
		Min = 0.02			Min = 3.5
		Max = 0.138			Max = 4.5
		Modus = 0.049			Modus = 4.0
CO ₂ Footprint	VRFB+SC	Triangular Distribution:	Critical raw materials	VRFB+SC	Triangular Distribution:
		Min = 0.021			Min = 3.5
		Max = 0.13			Max = 4.5
		Modus = 0.05			Modus = 4.0
CO ₂ Footprint	LFP	Triangular Distribution:	Critical raw materials	LFP	Triangular Distribution:
		Min = 0.008			Min = 3.5
		Max = 0.053			Max = 4.5
		Modus = 0.021			Modus = 3.5

CO ₂ Footprint	SiB PbA	Triangular Distribution:	Critical raw materials	SiB PbA	Triangular Distribution:
		Min = 0.013			Min = 1.5
		Max = 0.088			Max = 2.5
		Modus = 0.035			Modus = 2.0
Investment costs	VRFB	Triangular Distribution:	Round trip efficiency	VRFB	Triangular Distribution:
		Min = 1394.0			Min = 70.0
		Max = 8987.0			Max = 84.0
		Modus = 3549.0			Modus = 75.0
Investment costs	VRFB+SC	Triangular Distribution:	Round trip efficiency	VRFB+SC	Triangular Distribution:
		Min = 984.0			Min = 65.0
		Max = 6461.0			Max = 80.0
		Modus = 2522.0			Modus = 74.0
Investment costs	LFP	Triangular Distribution:	Round trip efficiency	LFP	Triangular Distribution:
		Min = 561.0			Min = 5.0
		Max = 3610.0			Max = 95.0
		Modus = 1424.0			Modus = 92.0
Investment costs	SiB PbA	Triangular Distribution:	Round trip efficiency	SiB PbA	Triangular Distribution:
		Min = 561.0			Min = 85.0
		Max = 3618.0			Max = 95.0
		Modus = 1425.0			Modus = 92.0
LCOS	VRFB	Triangular Distribution:	Durability (lifetime)	VRFB	Triangular Distribution:
		Min = 18.11			Min = 10000.0
		Max = 116.0			Max = 18000.0
		Modus = 46.0			Modus = 15000.0
LCOS	VRFB+SC	Triangular Distribution:	Durability (lifetime)	VRFB+SC	Triangular Distribution:
		Min = 13.19			Min = 15000.0
		Max = 86.6			Max = 20000.0
		Modus = 33.8			Modus = 18000.0
LCOS	LFP	Triangular Distribution:	Durability (lifetime)	LFP	Triangular Distribution:
		Min = 7.4			Min = 4000.0
		Max = 47.0			Max = 10000.0
		Modus = 18.8			Modus = 6000.0
LCOS	SiB PbA	Triangular Distribution:	Durability (lifetime)	SiB PbA	Triangular Distribution:
		Min = 7.6			Min = 3000.0
		Max = 49.5			Max = 8000.0
		Modus = 19.5			Modus = 4000.0
Safety awareness and public trust	VRFB	Triangular Distribution:	Distribution network	VRFB	Triangular Distribution:
		Min = 4.0			Min = 3.0
		Max = 5.0			Max = 4.5
		Modus = 5.0			Modus = 3.0
Safety awareness and public trust	VRFB+SC	Triangular Distribution:	Distribution network	VRFB+SC	Triangular Distribution:
		Min = 4.0			Min = 4.0
		Max = 5.0			Max = 5.0
		Modus = 5.0			Modus = 5.0

Safety awareness and public trust	LFP	Triangular Distribution:	Distribution network	LFP	Triangular Distribution:
		Min = 2.0			Min = 4.0
		Max = 4.0			Max = 5.0
		Modus = 3.5			Modus = 4.0
Safety awareness and public trust	SiB PbA	Triangular Distribution:	Distribution network	SiB PbA	Triangular Distribution:
		Min = 3.0			Min = 3.0
		Max = 4.0			Max = 5.0
		Modus = 4.0			Modus = 4.0
EU production share in the value chain	VRFB	Triangular Distribution:	Visual impact	VRFB	Triangular Distribution:
		Min = 2.0			Min = 2.5
		Max = 3.0			Max = 3.5
		Modus = 2.0			Modus = 3.0
EU production share in the value chain	VRFB+SC	Triangular Distribution:	Visual impact	VRFB+SC	Triangular Distribution:
		Min = 2.0			Min = 2.0
		Max = 3.0			Max = 4.0
		Modus = 2.0			Modus = 3.0
EU production share in the value chain	LFP	Triangular Distribution:	Visual impact	LFP	Triangular Distribution:
		Min = 1.0			Min = 1.5
		Max = 2.5			Max = 2.5
		Modus = 1.5			Modus = 2.0
EU production share in the value chain	SiB PbA	Triangular Distribution:	Visual impact	SiB PbA	Triangular Distribution:
		Min = 2.0			Min = 1.5
		Max = 3.0			Max = 2.5
		Modus = 2.0			Modus = 2.0
Circularity	VRFB	Triangular Distribution:	Reaction time	LFP	Triangular Distribution:
		Min = 4.0			Min = 4.0
		Max = 5.0			Max = 4.5
		Modus = 5.0			Modus = 4.0
Circularity	LFP	Triangular Distribution:	Reaction time	SiB PbA	Triangular Distribution:
		Min = 1.0			Min = 4.0
		Max = 3.0			Max = 4.5
		Modus = 2.0			Modus = 4.0
Circularity	SiB PbA	Triangular Distribution:			
		Min = 1.0			
		Max = 3.0			
		Modus = 2.0			

ANNEX II

In general, several case studies have been identified and developed to illustrate the application of hybrid energy storage systems across diverse sectors, including industry, grid services, off-grid systems, transportation, and buildings and have been presented in the roadmap and in D 4.2 for different sustainability assessment methods. Furthermore, some of these case studies have been compiled with the support of experts from the StoRIES project and contribute to the published book “Hybrid Energy Storage: Case Studies for the Energy Transition” [103], submitted to Springer Nature. The use case here is based on the interlinked workshop series and the results derived by these highly interactive workshops as shown in Table 1. In particular, the results from Workshop #3 are used to build the example use case using the identified KPIs.

Goal and scope of a participatory workshop

A participatory workshop was conducted to assess the sustainability and practical application of hybrid energy storage systems (HES) based on a practical use case, namely the hybrid energy storage using aluminium-air batteries as an example, but was not limited to this technology. The expected outcomes of the workshop were as follows:

- Addressing the challenges in the formulation of business models for hybrid energy storage concepts.
- Observing the use case specific variations on stakeholder requirements
- Identifying techno-economic, environmental and social challenges of ES
- Combining expert knowledge with stakeholder perspectives to evaluate technical performance, explore potential use cases, and co-create viable business models emphasizing interactivity, inclusiveness, and real-world relevance
- Providing a guided process through which participants could progressively build a shared understanding of the opportunities and challenges associated with HES technologies.

Each pillar contains specific indicators or criteria that relate to the performance of the storage system as displayed in Table 3. However, it is important to mention that each project may require a different set of KPIs, making this a continuous task.

Overall approach and workshop design

The workshop was organized around four real-world use cases with four groups, each representing a distinct energy storage challenge. These included in a mixed in person and online format:

- Emergency power backup for critical infrastructure, (in person)
- Integration into residential and commercial microgrids, (in person)
- Seasonal energy storage for district heating and electricity systems. (in person)
- Remote, Off-Grid Industrial Operations (online group)

Participants were assigned to one of these scenarios and worked in cross-disciplinary groups comprising researchers, industry representatives, policy experts, and civil society stakeholders. This setup ensured that diverse perspectives were embedded in the discussions from the outset. These cases propose were very different and require different energy vectors, operation hours and system set ups. The Use case on Residential and commercial microgrids was selected to display how the workshop was carried out and to provide some insights to the results. In the following the entire process is described in detail taking only the results from the group on commercial microgrids. An overview of the procedure is provided in Figure 13.

1-2 Preparation phase: the workshop requires a significant effort for preparation to identify relevant criteria and alternatives (See D 4.2.). The information derived in this phase can be used to structure and carry out the sustainability assessment itself. This step has to be carried out in an iterative way as there might be several changes in the discussion with stakeholders.

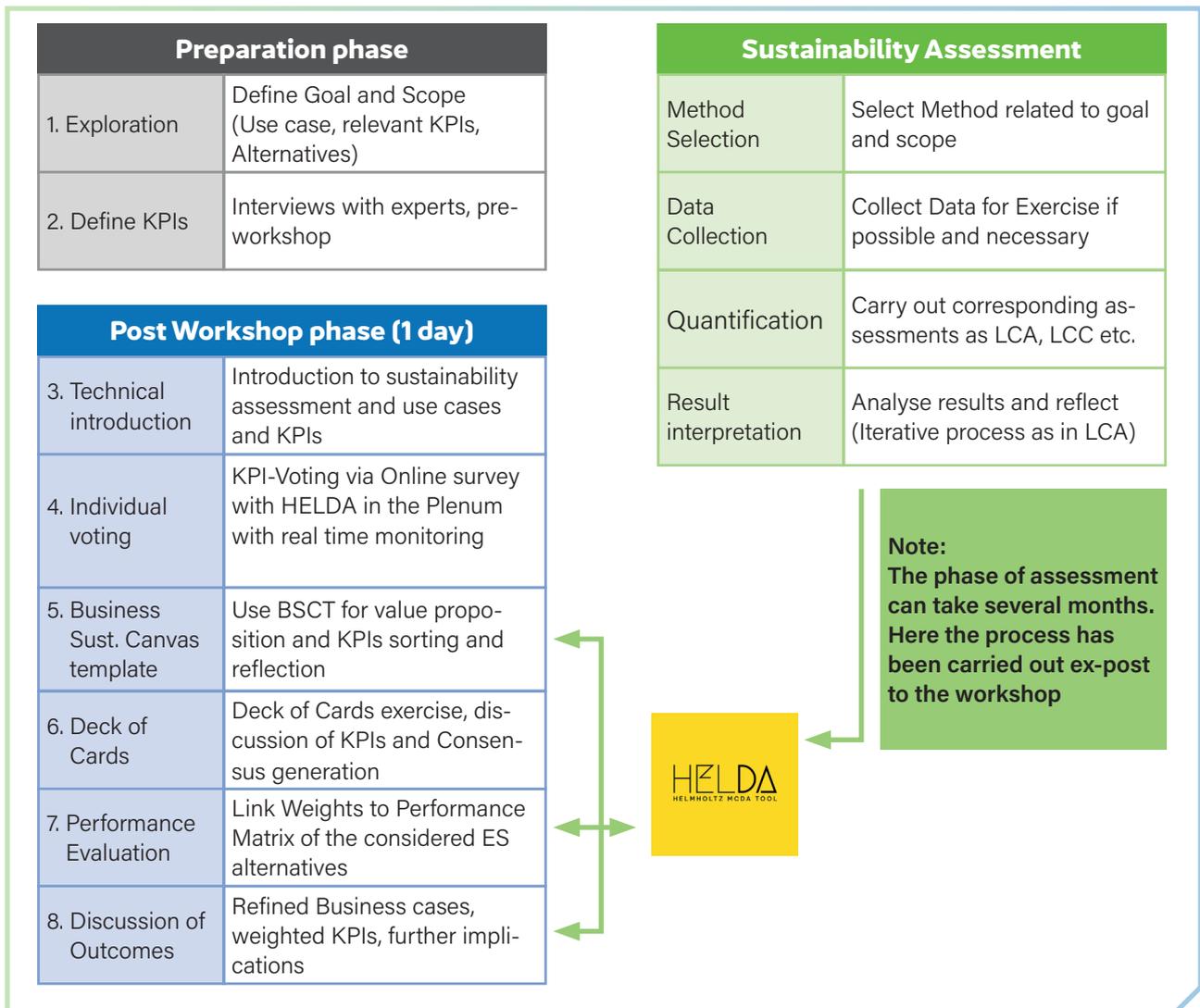
Sustainability Assessment: As mentioned, the preparation phase helps to structure the assessment itself, by e.g. selecting appropriate methods that fit the purpose. Of course, this selection has to consider the practicability of the method, the availability of data and finally assure sufficient resources in terms of time and money. HELDA as a software can be used to translate and combine the results from e.g. LCA to the preferences of the stakeholders during the workshop.

3 Technical introduction: Following the technical briefing, participants were presented with a set of sustainability-oriented Key Performance Indicators (KPIs), developed through prior research within the project. These indicators spanned from environmental, technical, economic, and social dimensions, covering aspects such as CO₂ footprint, durability, safety perception, circularity, and affordability and are application neutral. In addition, a technical introduction to the use cases and the targeted technology was given. This foundation helped to engage meaningfully with the subsequent evaluation steps.

4. Individual preferences: Each group then took part in an online survey session to 1) identify which KPIs they considered relevant to their specific use case or application respectively (individual voting) and 2) give relative importance to the proposed KPIs (individual weighting). This initial prioritization offered a snapshot of stakeholder values and expectations before deeper dialogue.

5. Business sustainability Canvas template exercise: Building on Deck of Card (DoC), the next step focused on developing practical business models. Using a guided Business Sustainability Canvas Template (BSCT), groups mapped out value propositions, customer segments, revenue strategies, and potential risks (see section XY). This exercise helped participants shift from abstract evaluation to concrete application, exploring how the HESS technology could deliver benefits and face challenges, within different operational and market contexts.

Figure 13: Overview of the overall process and approach. Note, the assessment should ideally take place in advance of the workshop to provide discussable results, this was not the case in carried out workshop.



6. Deck of Cards: The final phase of the workshop used a card-based group weighting exercise to facilitate group-based prioritization of the KPIs. Known as the “deck of cards” [101] method, this format encouraged each group to collectively assign relative importance to the various indicators, reflecting the insights gained during earlier discussions. It became clear that this collaborative step led to a more balanced and nuanced understanding of sustainability trade-offs, as participants refined their perspectives through dialogue and mutual reasoning.

7. Performance evaluation: This step has been carried out ex-post to the workshop using secondary data and own models to attribute performance values to the identified KPIs. Ideally this should be part of the workshop as it allows a comprehensive discussion of the results and potentially of the assumptions made by the analysts. This can lead to a recalculation of KPIs and can be helpful to assure a robust evaluation.

8. Discussion of Outcomes: By moving from individual preferences to collective judgment, the workshop structure promoted transparency, reflection, and practical relevance. It enabled participants to explore not just which indicators matter, but why they matter and how they interact in real-world deployment scenarios. The result was not only a set of business cases and weighted evaluation criteria, but also a tested process for inclusive, systems-oriented technology assessment.

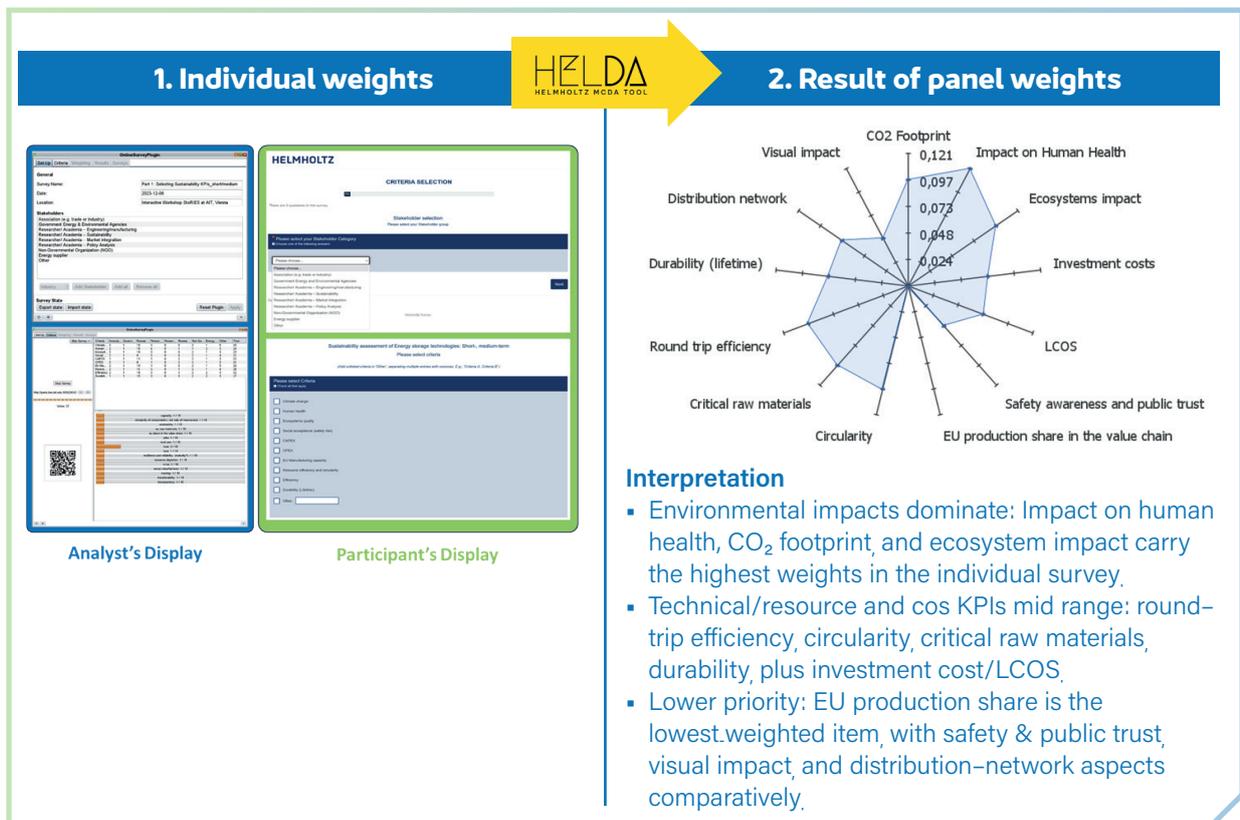
Workshop Results

The workshop revealed valuable insights into how diverse hybrid energy storage HESS use cases are perceived through technical, economic, environmental, and social perspectives. Despite the differing contexts of each working group, ranging from critical infrastructure backup to residential microgrids and district-scale seasonal storage, several cross-cutting themes and standout findings emerged.

Individual weighting

The first exercise was to collect individual priorities of all workshop members in general. This was done via an HELDA's online survey plugin, scannable via QR code. Here the participants filled out a survey, wherein they ticked relevant criteria, and could propose new ones. After that, relative weights had to be attributed to a scale from 1-10, for predefined criteria. Finally, results were then collected to plot the preferences within a spider plot as displayed in Figure 14 using HELDA.

Figure 14: results of the individual weighting based on HELDA [93]



The general weighting (dot-voting on KPIs like CO₂ footprint, durability, efficiency, etc.) captured individual preferences before deep discussions. These discussions represent the unfiltered priorities of participants likely based on their domain background, institutional perspective, or immediate concerns.

Sustainability Business Model Canvas exercise

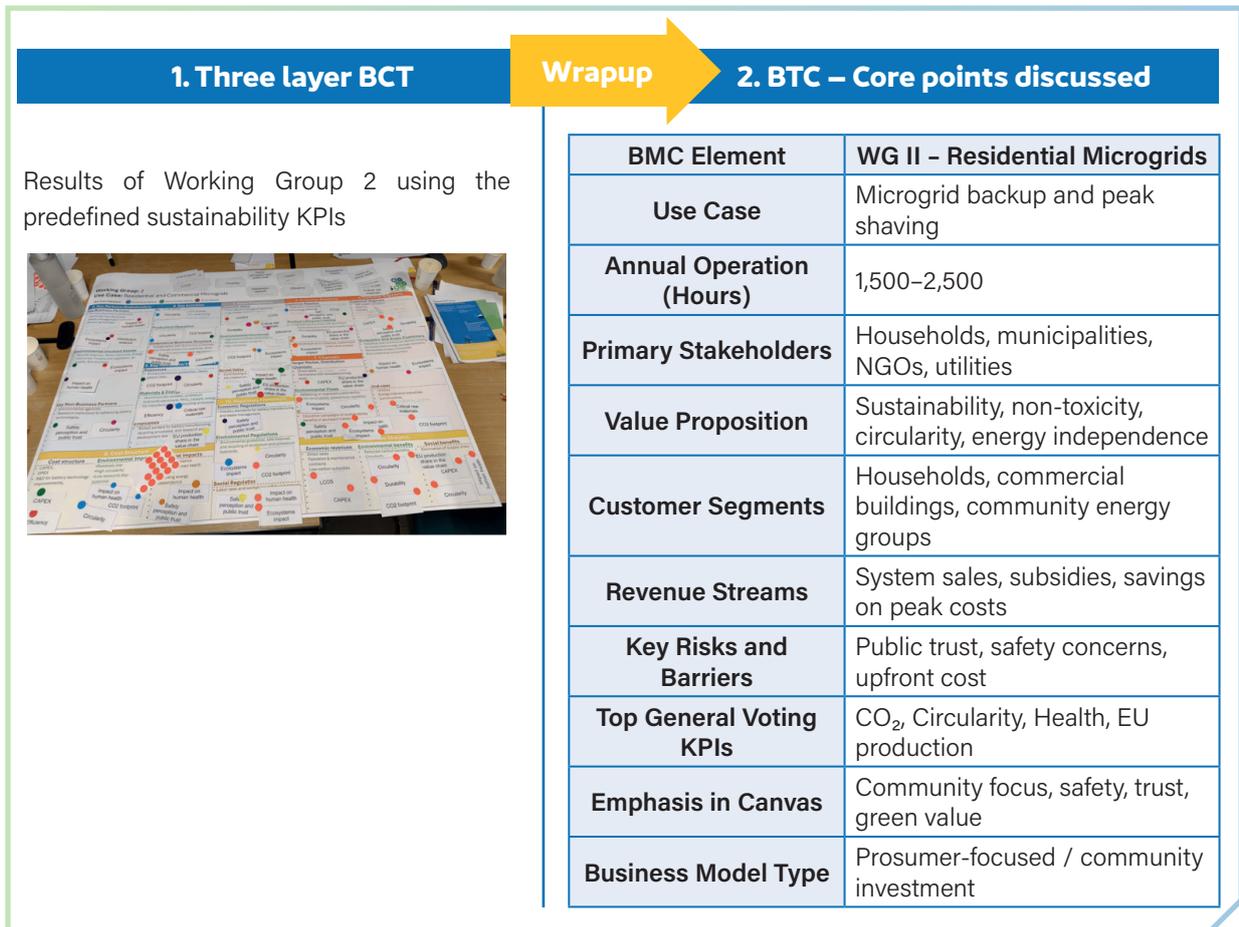
When participants developed the BSCT for their use cases, they began to apply those preferences to a specific technological and operational context, in this case the before presented KPIs in Table 2, with different application examples. This has provided a significant step in the process of the workshop as it:

- bridged abstract priorities with real-world HESS system design.

- discussions on BMC clearly incorporated many KPIs from the general voting but began to expand beyond them: new concerns like maintenance, regulatory barriers, response time, and waste heat utilization emerged often specific to the use case.

The three BMC results of the corresponding to WG I (Critical Infrastructure), WG II (Residential/Commercial Microgrids), and WG III (Seasonal Storage for District Energy Systems), offer insight into how stakeholder groups contextualized the use case within their specific, predefined use cases. These canvases can be analyzed against the general weights from the spider diagrams and the follow up Deck of Cards results to understand how stakeholder priorities were reflected in business model development. Each BSCT not only maps stakeholders but also reflects the core value propositions, business cases, and deployment logics across three distinct use cases. By comparing them, important insights into how different application contexts shape the perception of value, customer segments, and market opportunities can be extracted. An overview of the BSCT for WG 2 and its results can be found in Figure 15. In brief WG2 stressed affordability, modularity, and energy independence at the household and small business level.

Figure 15: Picture of the Business Canvas Template for WG 1 – 3 with first interpretation



Deck of Cards exercise

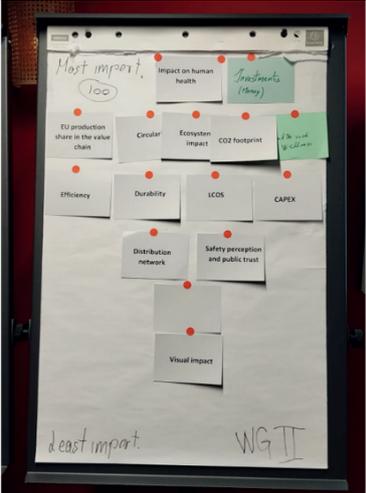
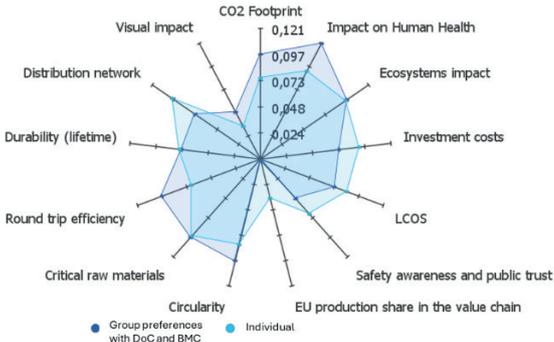
Because the Deck of Cards exercise happened after the BSCTs, it served as a reflective, synthesis-based activity. Up to now the participants have learned from technical presentations, assigned relative individual weights to KPIs, engaged in discussions and evaluated trade-offs in the BSCT. So, the deck of cards weights reflects mature, negotiated priorities, balancing individual opinions with use case realities, technical features and emerging group consensus. The MCDA-based prioritization helped participants identify viable pathways HESS adoption in each scenario, here the residential grid case.

Figure 16: Example for the discussion of WG II on the sorting of criteria based on the BCT exercise

1. Deck of Cards exercise	2. Relevance of the BSC and DoC combination
<p>Example of KPI re-ranking by one working group using the deck-of-cards method after the Business Sustainability Canvas exercise.</p> 	<p>Why it matters: Deliberation broadened priorities beyond initial individual votes; new criteria surfaced from the BSC context.</p> <p>Consensus shifts: CO₂ footprint remains a top concern across WGs; circularity, safety perception and EU production share gained weight through discussion.</p> <p>Use-case anchoring: Priorities reflect the assigned scenario (e.g., residential/commercial microgrid), not just generic technology preferences.</p>

An example of the follow up ranking of criteria with the DoC methods is provided in Figure 16, left. These cards represent how participants physically ranked various key performance indicators (KPIs) through sorting and discussion. The conversion of the DoC using the predefined KPIs resulted in the different prioritizations of criteria, which differed significantly across the use cases. The radar plot created by HELDA displayed in Figure 17 shows how the WG II on Residential Microgrid, prioritised various KPIs after group discussion (e.g. Critical raw materials were set equal to circularity). These results contrast with the previous individual weightings, where participants independently rated the importance of each criterion.

Figure 17: Deck of Card exercise (left) , comparison of single/Individual weights and the group weight via DoC (right)

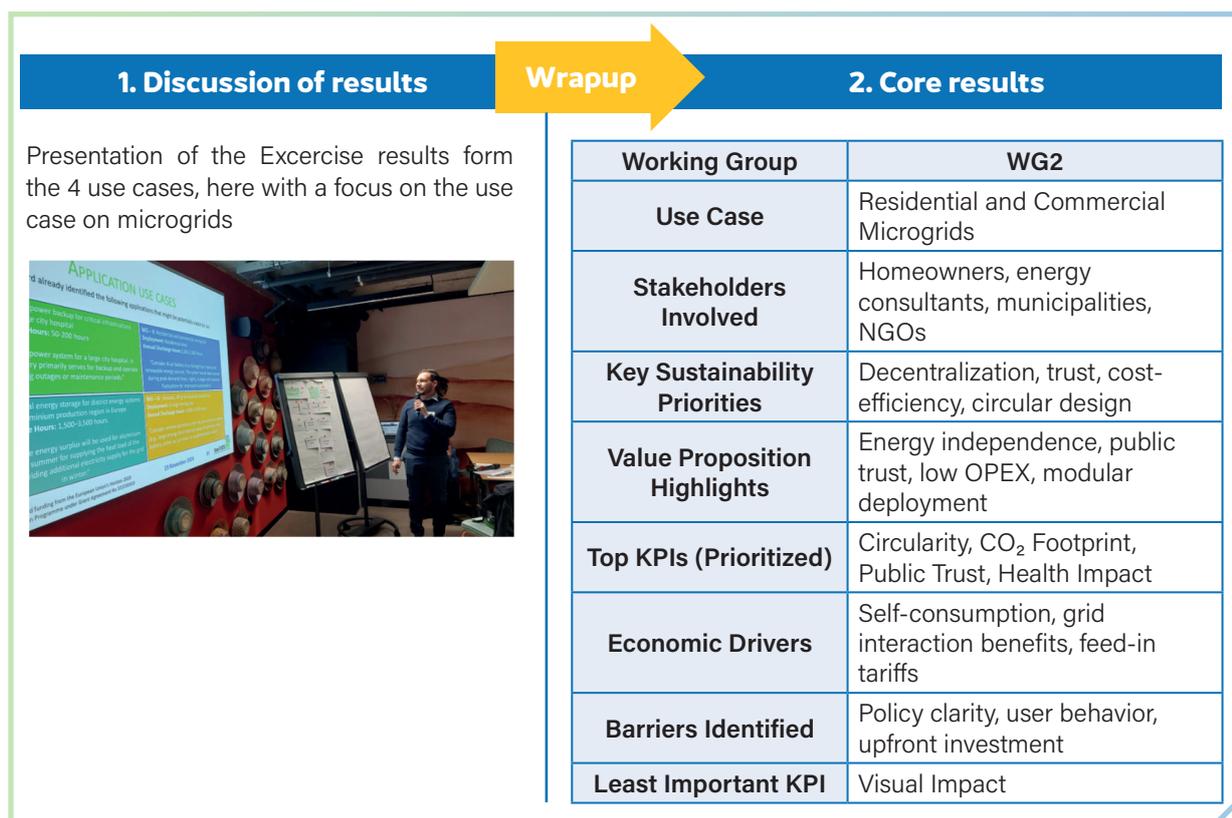
1. Deck of Cards Exercise	2. Attributed weights via HELDA
	 <p>Interpretation</p> <ul style="list-style-type: none"> Shared weights: Impact on Human Health, CO₂ Footprint, and Ecosystems impact rank highest (both the individual survey and the post.BSC/DoC) Shifts after BSC/DoC: more weight on implementation/cost KPIs, Distribution network, Investment costs, and LCOS and down-weights Circularity, Critical raw materials, Round-trip efficiency Persistently low: EU production share and Visual impact; Safety awareness & public trust ticks up slightly but stays lower-middle.

What stands out immediately is that group discussion significantly influenced the weighting outcomes. While individual responses in WG II previously showed a strong leaning toward technical and economic factors such as efficiency and durability, the group-based outcome is more balanced. Indicators like circularity, safety perception, and EU production share which received little attention individually gain visibility. This shift suggests that discussion helped integrate broader concerns, likely from members with different expertise or perspectives. In other words, the deliberation process fostered compromise and more inclusive decision-making.

Discussion of the exercise results

The final discussion clearly demonstrated that the participative approach significantly contributed to consensus-building and harmonized initially diverging viewpoints. The methodological combination of MCDA, Business Canvas, and Deck-of-Cards was highlighted as particularly useful for developing practical business models and realistic KPI prioritizations. The plenary discussion facilitated a final reflection and validation of the developed outcomes, especially concerning technical feasibility and social acceptance. An example of a result presentation is provided in Figure 18, including a wrap up of major discussion points for WG II.

Figure 18: Example of a final result presentation for one WG during the interactive workshop



Conclusion

Within the initial online survey, individual raw priorities were captured at the outset, participants engaged in a relative weighting exercise using a point scale to identify the most important evaluation criteria. This activity revealed each group's initial, unfiltered preferences, shaped by professional background and institutional perspectives. For example, WG II highlighted efficiency and circularity, while WG III emphasized CO₂ footprint and affordability. This phase established a baseline of values before any technical deep dives or collaborative modelling took place. Next, stakeholders translated these initial priorities into practice by building Business Model Canvases tailored to their assigned use cases, emergency backup, residential microgrids, and seasonal storage. During this phase, participants began to contextualize KPIs based on technological features and operational needs. Discussions revealed new layers of insight, including public trust and social value. This exercise encouraged cross-disciplinary dialogue, making space for broader considerations such as energy security, regulatory compliance, and community benefits. Finally, the Deck of Cards exercise prompted each group to collectively rank and weight evaluation criteria. Crucially, this step occurred after the BCT discussions, allowing stakeholders to reflect on earlier insights and negotiate a shared understanding of what matters most. Compared to the individual weighting, the results showed a more balanced and inclusive prioritization which gave more weight to safety, circularity, and public trust. The exercise successfully demonstrated the strength of a co-creative, participatory approach in designing sustainable energy solutions. It validated the Business Sustainability Canvas and KPI-based MCDA as effective tools for collaborative decision-making, capable of capturing trade-offs across technical, economic, environmental, and social dimensions. As such, this process lays a strong foundation for future implementation and scaling of hybrid energy storage technologies across Europe and beyond.

LITERATURE



10

1. General Assembly, "Resolution Adopted by the General Assembly on 11 September 2015," N. Y. U. N., 2015.
2. UNITED NATIONS, DEPARTMENT OF ECONOMIC, and United Nations Department of Economic and Social Affairs, "ACCELERATING SDG7 ACHIEVEMENT - Policy Briefs in Support of The First SDG7 Review at the UN High-Level Political Forum," United Nations, 2018.
3. "A Guide to SDG Interactions: From Science to Implementation," International Council for Science (ICSU), May 2017. Doi: 10.24948/2017.01.
4. IEA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach," IEA, Paris, 2023. [Online]. Available: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>.
5. IEA, "Tracking Clean Energy Progress 2023," International Energy Agency, Paris, 2023. [Online]. Available: <https://www.iea.org/reports/tracking-clean-energy-progress-2023>
6. European Association for Storage of Energy (EASE), "Energy Storage Targets 2030 and 2050: Ensuring Europe's Energy Security in a Renewable Energy System," European Association for Storage of Energy (EASE), 2022.
7. StoRIES Editors and Authors Group, Strategic Research and Innovation Agenda on Hybrid Energy Storage, June 2025, Available: https://www.eera-set.eu/index.php?option=com_attachments&task=download&id=1956:Working-Document---DO-NOT-DUPLICATE---StoRIES-SRIA
8. European Commission, Directorate-General for Environment, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Chemicals Strategy for Sustainability Towards a Toxic-Free Environment, Vol. 2020/667. 2020. Accessed: Nov. 25, 2023. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0667>
9. European Parliament, Council of the European Union, Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC (Text with EEA Relevance). 2023. [Online]. Available: <https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng>

10. D. Aschermayr et al., "Battery Passport Content Guidance - Achieving Compliance with the EU Battery Regulation and Increasing Sustainability and Circularity," Federal Ministry for Economic Affairs and Climate Action, Apr. 2023. [Online]. Available: https://thebattery.pass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance.pdf
11. Farhidi, F. Impact of Fossil Fuel Transition and Population Expansion on Economic Growth. *Environ Dev Sustain* **2023**, *25*, 2571–2609, doi:10.1007/s10668-022-02122-y.
12. Frate, G.F.; Ferrari, L.; Desideri, U. Energy Storage for Grid-Scale Applications: Technology Review and Economic Feasibility Analysis. *Renew Energy* **2021**, *163*, 1754–1772, doi:10.1016/j.renene.2020.10.070.
13. Gür, T.M. Review of Electrical Energy Storage Technologies, Materials and Systems: Challenges and Prospects for Large-Scale Grid Storage. *Energy Environ Sci* **2018**, *11*, 2696–2767, doi:10.1039/C8EE01419A.
14. Burian, O.; Dančová, P. Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) Technologies—A Comparison Review of Technology Possibilities. *Processes* **2023**, *11*, 3061, doi:10.3390/pr11113061.
15. Sankhe, S.; Krishna, S.V.M.; JUTURU, R.M.; Subrahmanyam, C. Power-to-X (PtX) Technologies and Their Potential Role in the Transition towards a Fossil-Free Energy Future: A Review of EFuels Synthesis and Direct Air Capture (DAC) Technology.; May 25 2023.
16. Sepulveda, N.A.; Jenkins, J.D.; Edington, A.; Mallapragada, D.S.; Lester, R.K. The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems. *Nat Energy* **2021**, *6*, 506–516, doi:10.1038/s41560-021-00796-8.
17. Escamilla, A.; Sánchez, D.; García-Rodríguez, L. Assessment of Power-to-Power Renewable Energy Storage Based on the Smart Integration of Hydrogen and Micro Gas Turbine Technologies. *Int J Hydrogen Energy* **2022**, *47*, 17505–17525, doi:10.1016/j.ijhydene.2022.03.238.
18. Directorate-General For Energy, "Database of the European Energy Storage Technologies and Facilities." [Object Object], 2020. Doi: 10.2906/101110101114/1.
19. Yang, Z.; Zhang, J.; Kintner-Meyer, M.C.W.; Lu, X.; Choi, D.; Lemmon, J.P.; Liu, J. Electrochemical Energy Storage for Green Grid. *Chem Rev* **2011**, *111*, 3577–3613, doi:10.1021/cr100290v.
20. Neto, P.A.N.; Soares, B.M.W.; da Silva, J.G.A.; Gehrke, C.S.; da Silva, I.R.F.M.P. Control of Hybrid Energy Storage System for Providing Grid Support Services. In Proceedings of the 2021 Brazilian Power Electronics Conference (COBEP); IEEE, November 7 2021; pp. 1–5.
21. Denholm, P.; Hummon, M. *Simulating the Value of Concentrating Solar Power with Thermal Energy Storage in a Production Cost Model*; Golden, CO (United States), 2012;
22. Barelli, L.; Bidini, G.; Cherubini, P.; Micangeli, A.; Pelosi, D.; Tacconelli, C. How Hybridization of Energy Storage Technologies Can Provide Additional Flexibility and Competitiveness to Microgrids in the Context of Developing Countries. *Energies (Basel)* **2019**, *12*, 3138, doi:10.3390/en12163138.
23. Hjalmarsson, J.; Thomas, K.; Boström, C. Service Stacking Using Energy Storage Systems for Grid Applications – A Review. *J Energy Storage* **2023**, *60*, 106639, doi:10.1016/j.est.2023.106639.

24. Ersoy, H.; Baumann, M.; Barelli, L.; Ottaviano, A.; Trombetti, L.; Weil, M.; Passerini, S. Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services. *Adv Mater Technol* **2022**, *7*, doi:10.1002/admt.202101400.
25. J. Elkington, “25 Years Ago I Coined the Phrase ‘Triple Bottom Line.’ Here’s Why It’s Time to Rethink It,” Harvard Business Review, Accessed: Apr. 18, 2024. [Online]. Available: <https://hbr.org/2018/06/25-years-ago-i-coined-the-phrase-triple-bottom-line-heres-why-im-giving-up-on-it>.
26. 26. Lönngren, J.; van Poeck, K. Wicked Problems: A Mapping Review of the Literature. *International Journal of Sustainable Development & World Ecology* **2021**, *28*, 481–502, doi:10.1080/13504509.2020.1859415.
27. J. Elkington, “The Triple Bottom Line,” Environ. Manag. Read. Cases, Vol. 2, Pp. 49–66, 1997.
28. Tavanti, M. The Future of Sustainability Management. In; 2023; pp. 325–337.
29. Isil, O.; Hernke, M.T. The Triple Bottom Line: A Critical Review from a Transdisciplinary Perspective. *Bus Strategy Environ* **2017**, *26*, 1235–1251, doi:10.1002/bse.1982.
30. Robinson, J. Squaring the Circle? Some Thoughts on the Idea of Sustainable Development. *Ecological Economics* **2004**, *48*, 369–384, doi:10.1016/j.ecolecon.2003.10.017.
31. K. Mori, “Global Justice in the Anthropocene: The Fourth Pillar Debate in Sustainable Development,” 77, Pp. 101–122, 2014.
32. European Commission, A New Circular Economy Action Plan for a Cleaner and More Competitive Europe, COM(2020)98 Final, 2020.
33. StoRIES Editors and Authors Group, Technology Roadmap for Hybridisation of Energy Storage, June 2025.
34. Zhou, A.; Li, X.; Ren, X.; Li, X.; Gu, C. Evaluation of the Performance and Economy for a Hybrid Energy Storage System Using Hydrogen and Compressed Carbon Dioxide as the Energy Carrier. *Energy Convers Manag* **2022**, *264*, 115700, doi:10.1016/j.enconman.2022.115700.
35. Akbar, A.; Majid, M.A.B.A.; Mokhtar, A.A. Life Cycle Costing of Thermal Energy Storage System Using CAPEX and OPEX. *Journal of Mechanical Science and Technology* **2021**, *35*, 3223–3229, doi:10.1007/s12206-021-0642-9.
36. Barelli, L.; Bidini, G.; Ciupageanu, D.A.; Pelosi, D. Integrating Hybrid Energy Storage System on a Wind Generator to Enhance Grid Safety and Stability: A Levelized Cost of Electricity Analysis. *J Energy Storage* **2021**, *34*, 102050, doi:10.1016/j.est.2020.102050.
37. Zhang, Y.; Johansson, P.; Kalagasidis, A.S. Techno-Economic Assessment of Thermal Energy Storage Technologies for Demand-Side Management in Low-Temperature Individual Heating Systems. *Energy* **2021**, *236*, 121496, doi:10.1016/j.energy.2021.121496.
38. Schmidt, O.; Melchior, S.; Hawkes, A.; Staffell, I. Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule* **2019**, *3*, 81–100, doi:10.1016/j.joule.2018.12.008.
39. Baumann, M.; Peters, J.F.; Weil, M.; Grunwald, A. CO₂ Footprint and Life Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications. *Energy Technology* **2017**, *5*, 1071–1083, doi:10.1002/ente.201600622.

40. Obi, M.; Jensen, S.M.; Ferris, J.B.; Bass, R.B. Calculation of Levelized Costs of Electricity for Various Electrical Energy Storage Systems. *Renewable and Sustainable Energy Reviews* **2017**, *67*, 908–920, doi:10.1016/j.rser.2016.09.043.
41. Jülch, V. Comparison of Electricity Storage Options Using Levelized Cost of Storage (LCOS) Method. *Appl Energy* **2016**, *183*, 1594–1606, doi:10.1016/j.apenergy.2016.08.165.
42. Zakeri, B.; Syri, S. Electrical Energy Storage Systems: A Comparative Life Cycle Cost Analysis. *Renewable and Sustainable Energy Reviews* **2015**, *42*, 569–596, doi:10.1016/j.rser.2014.10.011.
43. Baumann, M.; Häringer, M.; Schmidt, M.; Schneider, L.; Peters, J.F.; Bauer, W.; Binder, J.R.; Weil, M. Prospective Sustainability Screening of Sodium Ion Battery Cathode Materials. *Adv Energy Mater* **2022**, *12*, doi:10.1002/aenm.202202636.
44. Wulf, C.; Zapp, P. Analyzing the Future Potential of Defossilizing Industrial Specialty Glass Production with Hydrogen by LCA. *Procedia CIRP* **2022**, *105*, 666–671, doi:10.1016/j.procir.2022.02.111.
45. Crenna, E.; Gauch, M.; Widmer, R.; Wäger, P.; Hirschier, R. Towards More Flexibility and Transparency in Life Cycle Inventories for Lithium-Ion Batteries. *Resour Conserv Recycl* **2021**, *170*, 105619, doi:10.1016/j.resconrec.2021.105619.
46. David, B.R.; Spencer, S.; Miller, J.; Almahmoud, S.; Jouhara, H. Comparative Environmental Life Cycle Assessment of Conventional Energy Storage System and Innovative Thermal Energy Storage System. *International Journal of Thermofluids* **2021**, *12*, 100116, doi:10.1016/j.ijft.2021.100116.
47. Peters, J.F.; Baumann, M.; Binder, J.R.; Weil, M. On the Environmental Competitiveness of Sodium-Ion Batteries under a Full Life Cycle Perspective – a Cell-Chemistry Specific Modelling Approach. *Sustain Energy Fuels* **2021**, *5*, 6414–6429, doi:10.1039/D1SE01292D.
48. L'Abbate, P.; Dassisti, M.; Olabi, A.G. Small-Size Vanadium Redox Flow Batteries: An Environmental Sustainability Analysis via LCA. In; 2019; pp. 61–78.
49. Cusenza, M.A.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M. Energy and Environmental Benefits of Circular Economy Strategies: The Case Study of Reusing Used Batteries from Electric Vehicles. *J Energy Storage* **2019**, *25*, 100845, doi:10.1016/j.est.2019.100845.
50. Mostert, C.; Ostrander, B.; Bringezu, S.; Kneiske, T.M. Comparing Electrical Energy Storage Technologies Regarding Their Material and Carbon Footprint. *Energies (Basel)* **2018**, *11*, 3386, doi:10.3390/en1123386.
51. Weil, M.; Ziemann, S.; Peters, J. The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles. In; 2018; pp. 59–74.
52. Ziemann, S.; Müller, D.B.; Schebek, L.; Weil, M. Modeling the Potential Impact of Lithium Recycling from EV Batteries on Lithium Demand: A Dynamic MFA Approach. *Resour Conserv Recycl* **2018**, *133*, 76–85, doi:10.1016/j.resconrec.2018.01.031.
53. Longo, S.; Antonucci, V.; Cellura, M.; Ferraro, M. Life Cycle Assessment of Storage Systems: The Case Study of a Sodium/Nickel Chloride Battery. *J Clean Prod* **2014**, *85*, 337–346, doi:10.1016/j.jclepro.2013.10.004.

54. Adeyeye, K.; Gallagher, J.; Ramos, H.M.; McNabola, A. The Social Return Potential of Micro Hydropower in Water Networks Based on Demonstrator Examples. *Energies (Basel)* **2022**, *15*, 6625, doi:10.3390/en15186625.
55. Baur, D.; Emmerich, P.; Baumann, M.J.; Weil, M. Assessing the Social Acceptance of Key Technologies for the German Energy Transition. *Energy Sustain Soc* **2022**, *12*, 4, doi:10.1186/s13705-021-00329-x.
56. Sánchez, A.; Zhang, Q.; Martín, M.; Vega, P. Towards a New Renewable Power System Using Energy Storage: An Economic and Social Analysis. *Energy Convers Manag* **2022**, *252*, 115056, doi:10.1016/j.enconman.2021.115056.
57. Bamana, G.; Miller, J.D.; Young, S.L.; Dunn, J.B. Addressing the Social Life Cycle Inventory Analysis Data Gap: Insights from a Case Study of Cobalt Mining in the Democratic Republic of the Congo. *One Earth* **2021**, *4*, 1704–1714, doi:10.1016/j.oneear.2021.11.007.
58. Bouillass, G.; Blanc, I.; Perez-Lopez, P. Step-by-Step Social Life Cycle Assessment Framework: A Participatory Approach for the Identification and Prioritization of Impact Subcategories Applied to Mobility Scenarios. *Int J Life Cycle Assess* **2021**, *26*, 2408–2435, doi:10.1007/s11367-021-01988-w.
59. Fett, D.; Dehler-Holland, J.; Schmutz, M. A Survey on the User Acceptance of PV Battery Storage Systems. *Sustainability Management Forum | NachhaltigkeitsManagementForum* **2021**, *29*, 161–171, doi:10.1007/s00550-021-00513-9.
60. Liu, J.; Yu, J.; Li, Y.; Yan, S.; Wei, Q. Social Effects Assessment of Photovoltaic-Coupled Energy Storage System Application Projects Based on EEEP: A Case Study from Northwest China. *Energy Reports* **2021**, *7*, 1239–1257, doi:10.1016/j.egyr.2021.09.139.
61. L. Mancini; N. A. Eslava; M. Traverso; F. Mathieux Assessing Impacts of Responsible Sourcing Initiatives for Cobalt: Insights from a Case Study. *Resour. Policy*, Vol. 71, p. 102015, 2021., doi:10.1016/j.resourpol.2021.102015.
62. Emmerich, P.; Hülemeier, A.-G.; Jendryczko, D.; Baumann, M.J.; Weil, M.; Baur, D. Public Acceptance of Emerging Energy Technologies in Context of the German Energy Transition. *Energy Policy* **2020**, *142*, 111516, doi:10.1016/j.enpol.2020.111516.
63. Thies, C.; Kieckhäfer, K.; Spengler, T.S.; Sodhi, M.S. Assessment of Social Sustainability Hotspots in the Supply Chain of Lithium-Ion Batteries. *Procedia CIRP* **2019**, *80*, 292–297, doi:10.1016/j.procir.2018.12.009.
64. J. Werker; C. Wulf; P. Zapp "Working Conditions in Hydrogen Production: A Social Life Cycle Assessment," *J. Ind. Ecol.*, Vol. 23, No. 5, Pp. 1052–1061, 2019.
65. B. Zimmermann, M. Baumann, J. Reiß, G. Rodriguez Garcia, and M. Weil, "Social Life Cycle Assessment as a Pillar of Sustainability Analysis of Batteries: The Case of LiFePO," 2015.
66. Amini Toosi, H.; Lavagna, M.; Leonforte, F.; Del Pero, C.; Aste, N. A Novel LCSA-Machine Learning Based Optimization Model for Sustainable Building Design-A Case Study of Energy Storage Systems. *Build Environ* **2022**, *209*, 108656, doi:10.1016/j.buildenv.2021.108656.
67. Baumann, M.; Peters, J.; Weil, M. Exploratory Multicriteria Decision Analysis of Utility Scale Battery Storage Technologies for Multiple Grid Services Based on Life Cycle Approaches. *Energy Technology* **2020**, *8*, doi:10.1002/ente.201901019.

68. Guo, Z.; Ge, S.; Yao, X.; Li, H.; Li, X. Life Cycle Sustainability Assessment of Pumped Hydro Energy Storage. *Int J Energy Res* **2020**, *44*, 192–204, doi:10.1002/er.4890.
69. Vogt Gwerder, Y.; Marques, P.; Dias, L.C.; Freire, F. Life beyond the Grid: A Life-Cycle Sustainability Assessment of Household Energy Needs. *Appl Energy* **2019**, *255*, 113881, doi:10.1016/j.apenergy.2019.113881.
70. Ren, J. Sustainability Prioritization of Energy Storage Technologies for Promoting the Development of Renewable Energy: A Novel Intuitionistic Fuzzy Combinative Distance-Based Assessment Approach. *Renew Energy* **2018**, *121*, 666–676, doi:10.1016/j.renene.2018.01.087.
71. Hienuki, S. Environmental and Socio-Economic Analysis of Naphtha Reforming Hydrogen Energy Using Input-Output Tables: A Case Study from Japan. *Sustainability* **2017**, *9*, 1376, doi:10.3390/su9081376.
72. Sanf elix, J.; De la R ua, C.; Schmidt, J.; Messagie, M.; Van Mierlo, J. Environmental and Economic Performance of an Li-Ion Battery Pack: A Multiregional Input-Output Approach. *Energies (Basel)* **2016**, *9*, 584, doi:10.3390/en9080584.
73. Daim, T.U.; Li, X.; Kim, J.; Simms, S. Evaluation of Energy Storage Technologies for Integration with Renewable Electricity: Quantifying Expert Opinions. *Environ Innov Soc Transit* **2012**, *3*, 29–49, doi:10.1016/j.eist.2012.04.003.
74. Cantono, S.; Heijungs, R.; Kleijn, R. Environmental Accounting of Eco-Innovations through Environmental Input–Output Analysis: The Case of Hydrogen and Fuel Cells Buses. *Economic Systems Research* **2008**, *20*, 303–318, doi:10.1080/09535310802346351.
75. W. Klopffer Life Cycle Sustainability Assessment of Products.02.376.
76. Sala, S. Triple Bottom Line, Sustainability and Sustainability Assessment, an Overview. In *Biofuels for a More Sustainable Future*; Elsevier, 2020; pp. 47–72.
77. R. E. Miller; P. D. Blair Input-Output Analysis: Foundations and Extensions. Cambridge University Press 2009.
78. Kalbar, P.P.; Das, D. Advancing Life Cycle Sustainability Assessment Using Multiple Criteria Decision Making. In *Life Cycle Sustainability Assessment for Decision-Making*; Elsevier, 2020; pp. 205–224.
79. Sala, S.; Ciuffo, B.; Nijkamp, P. A Systemic Framework for Sustainability Assessment. *Ecological Economics* **2015**, *119*, 314–325, doi:10.1016/j.ecolecon.2015.09.015.
80. Kulišić, B.; Loizou, E.; Rozakis, S.; Šegon, V. Impacts of Biodiesel Production on Croatian Economy. *Energy Policy* **2007**, *35*, 6036–6045, doi:10.1016/j.enpol.2007.08.025.
81. Lin, R.; Man, Y.; Ren, J. Life Cycle Decision Support Framework: Method and Case Study. In *Life Cycle Sustainability Assessment for Decision-Making*; Elsevier, 2020; pp. 175–204.
82. T. M. Bachmann et al. D1. 4 Critical Evaluation of Material Criticality and Product-Related Circularity Approaches 2021.
83. Finkbeiner, M.; Schau, E.M.; Lehmann, A.; Traverso, M. Towards Life Cycle Sustainability Assessment. *Sustainability* **2010**, *2*, 3309–3322, doi:10.3390/su2103309.

84. T. L. Saaty, "A Scaling Method for Priorities in Hierarchical Structures," *J. Math. Psychol.*, Vol. 15, No. 3, Pp. 234–281, 1977.
85. Brans, J.-P.; De Smet, Y. PROMETHEE Methods. In; 2016; pp. 187–219.
86. Versteeg, T.; Baumann, M.J.; Weil, M.; Moniz, A.B. Exploring Emerging Battery Technology for Grid-Connected Energy Storage with Constructive Technology Assessment. *Technol Forecast Soc Change* **2017**, *115*, 99–110, doi:10.1016/j.techfore.2016.09.024.
87. Baumann, M.; Weil, M.; Peters, J.F.; Chibeles-Martins, N.; Moniz, A.B. A Review of Multi-Criteria Decision Making Approaches for Evaluating Energy Storage Systems for Grid Applications. *Renewable and Sustainable Energy Reviews* **2019**, *107*, 516–534, doi:10.1016/j.rser.2019.02.016.
88. Beylot, A.; Secchi, M.; Cerutti, A.; Merciai, S.; Schmidt, J.; Sala, S. Assessing the Environmental Impacts of EU Consumption at Macro-Scale. *J Clean Prod* **2019**, *216*, 382–393, doi:10.1016/j.jclepro.2019.01.134.
89. Rodríguez-Serrano, I.; Caldés, N.; Rúa, C. de la; Lechón, Y. Assessing the Three Sustainability Pillars through the Framework for Integrated Sustainability Assessment (FISA): Case Study of a Solar Thermal Electricity Project in Mexico. *J Clean Prod* **2017**, *149*, 1127–1143, doi:10.1016/j.jclepro.2017.02.179.
90. Hu, J.; Wang, S.; Huang, K.; Wei, Q.; Chen, H. Spillover-Feedback Effects of Social, Economic, and Environmental Footprints Based on the "Belt and Road Initiative." *J Environ Manage* **2022**, *305*, 114414, doi:10.1016/j.jenvman.2021.114414.
91. "ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework," International Organization for Standardization, 2006a.
92. Fava, J.A.; Smerek, A.; Heinrich, A.B.; Morrison, L. The Role of the Society of Environmental Toxicology and Chemistry (SETAC) in Life Cycle Assessment (LCA) Development and Application. In; 2014; pp. 39–83.
93. L. M. Estrada; M. Haase; T. Müller HELDA. Germany. [Online]. Available: <https://www.mcda-helmholtz.de/64.php>
94. Heigl, E.-M.; Schäffer, M.; Zeilerbauer, L.; Zauner, A.; Lindorfer, J.; Ott, J.; Fischer, P. Life Cycle Assessment of a Novel Hybrid Energy Storage System: Environmental Hotspots and Sustainability Options Based on Experimental Insights. *J Energy Storage* **2025**, *132*, 117705, doi:10.1016/j.est.2025.117705.
95. Weber, A.Z.; Mench, M.M.; Meyers, J.P.; Ross, P.N.; Gostick, J.T.; Liu, Q. Redox Flow Batteries: A Review. *J Appl Electrochem* **2011**, *41*, 1137–1164, doi:10.1007/s10800-011-0348-2.
96. Minke, C.; Kunz, U.; Turek, T. Techno-Economic Assessment of Novel Vanadium Redox Flow Batteries with Large-Area Cells. *J Power Sources* **2017**, *361*, 105–114, doi:10.1016/j.jpowsour.2017.06.066.
97. Ciroth, A.; Muller, S.; Weidema, B.; Lesage, P. Empirically Based Uncertainty Factors for the Pedigree Matrix in Ecoinvent. *Int J Life Cycle Assess* **2016**, *21*, 1338–1348, doi:10.1007/s11367-013-0670-5.
98. Andreas Ciroth "Fehlerrechnung in Ökobilanzen," Technische Universität Berlin, Berlin 2001.
99. Mohr, M.; Peters, J.F.; Baumann, M.; Weil, M. Toward a Cell chemistry Specific Life Cycle Assessment of Lithium ion Battery Recycling Processes. *J Ind Ecol* **2020**, *24*, 1310–1322, doi:10.1111/jiec.13021.

100. Baur, D.; Baumann, M.J.; Stuhm, P.; Weil, M. Societal Acceptability of Large Stationary Battery Storage Systems. *Energy Technology* **2023**, *11*, doi:10.1002/ente.202201454.
101. Figueira, J.; Roy, B. Determining the Weights of Criteria in the ELECTRE Type Methods with a Revised Simos' Procedure. *Eur J Oper Res* **2002**, *139*, 317–326, doi:10.1016/S0377-2217(01)00370-8.
102. Hüseyin, E.; Baumann, M.J et al. D. 4.2. Common base for environmental, techno-economic and socio-economic assessment to un-lock the potential applications for hybrid ES (HES) systems 2024
103. Hybrid Energy Storage. (2025). In R. Scipioni, M. E. Gil Bardají, L. Barelli, M. Baumann, & S. Passerini (Eds.), *Lecture Notes in Energy*. Springer Nature Switzerland. <https://doi.org/10.1007/978-3-031-97755-8>

