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Empowering sustainability assessment of energy storage

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Energy storage (ES) plays a vital role in decarbonizing energy systems, yet its sustainability implications remain critical during its rapid deployment across mobile and stationary applications. This study presents the first systematic literature review focused on the assessment methods applied to ES systems in the sustainability context, by analyzing 205 peer-reviewed studies from the past five years. The review identifies Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) as the most commonly employed methods, with a strong technological focus on hydrogen-based systems and batteries. In contrast, a limited number of studies consider social aspects in the sustainability context. An increasing trend toward integrated economic and environmental assessments is observed, though their coherence is often limited due to the absence of a standardized methodological framework. Most studies apply narrow system boundaries, frequently omitting critical life cycle stages such as the use phase and end-of-life. This paper provides a methodological overview of applied approaches, summarizes key indicators and gaps, and offers recommendations to enhance the comprehensiveness of ES sustainability assessments. Additionally, targeted suggestions are delivered for practitioners, method developers and policy actors to improve the quality and applicability of future assessment practices.

1. Introduction

The energy transition necessitates widespread deployment of renewable energy at all scales to achieve climate neutrality and support sustainable development. By 2050, wind and solar PV are projected to supply approximately 70% of global electricity generation, raising the overall share of renewables to about 90% in the International Energy Agency's (IEAindex: IEA\t: International Energy Agency?>) Net-Zero Emissions by 2050 (NZE) scenario.[1] Although the NZE roadmap was designed to align with limiting the global mean temperature increase to 1.5 °C – an outcome now widely regarded as highly ambitious given current trends – it continues to serve as an authoritative reference for technical benchmarking, highlighting the scale of the required transformation. Notwithstanding, an energy system largely dependent on fluctuating renewables like PV and wind power requires flexibilization options to balance supply and demand. The expansion of energy storage (ES) capacities is expected to play a key role in meeting this need, leveraging both conventional and emerging ES technologies to ensure grid stability and system reliability. Consequently, the NZE scenario projects a significant global ramp-up in ES deployment until 2050.[2]

Pumped hydro storage (PHSindex: PHS\t: Pumped Hydro Storage?>) as a conventional large-scale ES alternative has the highest share of the total global installed storage capacity, reaching 181 GW in 2023, where the battery energy storage (BESindex: BES\t: Battery Energy Storage?>) shows a rapid increase in capacity additions reaching approximately 85 GW

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capacity.[2] The NZE scenario forecasts a global BES capacity demand of 3–5 TW by 2050, including electric vehicles, utility-scale batteries and behind-the-meter applications.[3] In contrast, hydrogen-based storage using electrolyzers remains in its early stages, providing 4 Mt H_2 with limited adoption to date. However, a substantial increase in low-carbon hydrogen production (through electrolysis and fossil fuels with carbon capture use and storage (CCUS)) is projected in the NZE scenario to supply 70 Mt H_2 by 2030, mainly supporting the demand for the hard-to-abate industry and hydrogen-based fuel production, as well as power generation.[1] These developments underscore the critical role of ES technologies in facilitating a global energy transition. However, the scale of adoption, particularly for BES and hydrogen storage, raises concerns regarding costs, supply chain constraints, resource availability, and environmental and social impacts.[4–6] Thus, uncertainties and risks associated with the long-term sustainability of these technologies remain unresolved.

Addressing these challenges requires comprehensive knowledge generation of the sustainability aspects of ES technologies to inform decision-making and promote their responsible integration. Given that sustainability is a multifaceted challenge, it is necessary to evaluate its economic, environmental and social dimensions in a systematic and transparent way. This emphasizes the need for robust assessment methods that provide reliable information to anticipate the long-term impacts of decisions made today.[7] Existing sustainability assessment approaches have been criticized for their methodological limitations, data availability and quality, as well as their contextual adaptability and comparability, all of which impact their effectiveness in guiding decision-making.[8,9] While current methods for evaluating the sustainability aspects of ES technologies have notable limitations, they remain the primary tools available for providing valuable insights. Given the growing significance of these technologies and their rapid large-scale adoption, such evaluation has become more critical than ever.

This study seeks to present an overview of the methodologies employed in the sustainability assessment of ES technologies, with a focus on the economic, environmental and social dimensions of sustainability, in order to observe the methods used and how they are applied in practice. Hence, a systematic review was conducted to analyze published peer-reviewed literature from the past five years in terms of methods, technological scope, impact dimensions, and indicators. The collected information from the studies is used as a basis to support discussion in terms of state-of-the-art assessment methods, identified research gaps, methodological recommendations and the capacity of the methods to address the sustainability of ES as a whole.

The findings offer valuable insights for researchers, industry stakeholders and policymakers, supporting informed decision-making and fostering cross-disciplinary dialogue on ES sustainability issues. By identifying both strengths and limitations of current assessment practices, this review contributes to the ongoing development of more effective and holistic sustainability evaluation frameworks for ES technologies.

2. Methodology

To ensure a systematic and comprehensive literature review of sustainability assessment methods for ES, the following search strategy was employed to identify relevant studies. The search was conducted using Lens Scholarly†, an academic database that indexes peer-reviewed journal articles, conference proceedings and other scholarly publications. The following Boolean search string was used to retrieve relevant studies:

Title: (“sustainability assessment” OR “sustainability evaluation” OR “life cycle” AND (environmental OR economic OR social OR “public acceptance”)) AND (“energy storage” OR “battery” OR “hydrogen” OR “ammonia” OR “thermal energy storage”) AND year_published: (2019 OR 2020 OR 2021 OR 2022 OR 2023 OR 2024).

The terms “sustainability assessment” OR “sustainability evaluation” were included in the title search to capture studies focusing on assessment methods. The addition of “life cycle” ensured the inclusion of assessments employing life cycle thinking, as this approach is used frequently for sustainability assessments. The phrases (environmental OR economic OR social OR “public acceptance”) were incorporated into the search string to ensure that studies addressing at least one of the three pillars of sustainability were captured. In this context, “public acceptance” is considered as a sub-aspect of the social dimension, since some studies address acceptance without explicitly framing it as a social criterion. The terms (“energy storage” OR “battery” OR “hydrogen” OR “ammonia” OR “thermal energy storage”) aimed to set the technological scope of the assessments. Specific terms such as battery, hydrogen or ammonia were included, since in many studies they are not combined with the keyword “energy storage”. Since the study aims to provide an overview of the assessment landscape, the filter on the timeframe covered the last five years (2019–2024) to capture recent advancements and up-to-date methods in sustainability assessment of ES.

The initial search query returned 424 studies, which were subjected to a multi-stage filtering process considering the inclusion or exclusion criteria. The main inclusion criterion was that the study employs an assessment method for the sustainability evaluation of ES technologies only on at least one sustainability dimension. First, a manual review of title and abstract was done based on the given criteria. After this refinement the number of collected studies was reduced to 205 *via* exclusion of irrelevant studies, non-peer reviewed studies and duplicates. Further processing and data extraction were conducted with the assistance of artificial intelligence, using a custom-trained GPT model, which was developed on the basis of ChatGPT. Using the model following predefined attributes were extracted from studies, and double-checked to ensure consistency and accuracy:

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† The Lens scholarly works MetaRecords include the following primary data sources: Crossref, PubMed, OpenAlex and Microsoft Academic (discontinued), with SI data from additional data sources including Unpaywall, OpenCitations, DOAJ, ORCID, ROR, PMC and publishers such as Springer Nature.

- Main technological category (*e.g.*, electrochemical, chemical, thermal energy storage),
- Assessed technology (*e.g.*, Li-ion battery, hydrogen, ammonia, compressed air energy storage),
- Assessed sustainability dimensions identifying the primary, secondary, and tertiary focus on economic, environmental, or social assessments,
- Applied assessment methods,
- Assessed system boundaries and chosen indicators.

All extracted information was systemically organized, and inconsistencies were resolved through iterative refinements, for instance unification of indicator or impact category terminology. For transparency reasons, the raw and refined collection, and extracted data is provided in the SI.

3. Energy storage within a transitioning global energy system

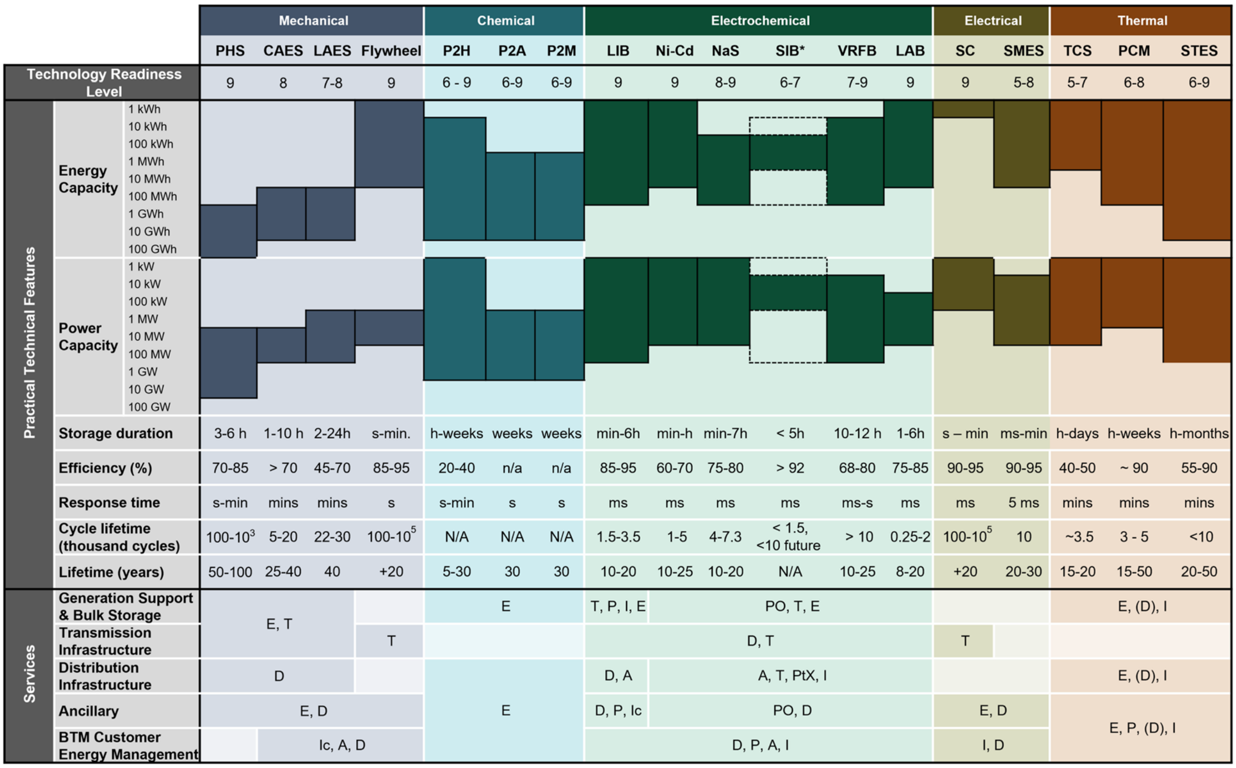
A sustainable energy transition requires measures on both the supply and demand sides. The widespread roll out of renewables can be considered as the most fundamental step of this transition, increasing the share of wind and solar power generation. However, their fluctuating generation characteristics can cause mismatches between demand and supply, which must be in balance at any time to guarantee safe energy provision. Imbalances must be tackled by flexibility capabilities at different levels in order to avoid supply security and reliability issues.

ES technologies are one of the flexibility options that can mitigate such mismatches by timely decoupling of demand and supply. Furthermore, the phase-out of fossil-based flexibilization options (*e.g.*, natural gas, coal, oil *etc.*) underpins the potential of ES to grant the required flexibility. Since the flexibility requirements of various services dictate different technical features, available and emerging ES technological alternatives need to be reconsidered for enhancing sustainability while ensuring the service-related technical criteria. Hence, one cannot identify a single technology that can fulfil the requirements of all applications, but rather a mixture of complementary technologies is needed. Fig. 1 provides a concise technical overview of conventional and emerging ES technologies based on the classifications and facilities listed in the Database of the European Storage Technologies and Facilities.[10] The overview includes technologies that are cataloged, operational, or under development, referring to their technical features, application fields and corresponding energy system actors. The technical features, project application fields and services presented are related to the maturity of the technology, hence for immature technologies projections are incorporated to the best knowledge of authors. In terms of application fields, regional deviations might occur due to differences in the market structure and value recognition of ES services.

As indicated in Fig. 1, ES technologies demonstrate distinct features (*e.g.*, reaction time, charge/discharge profile, or energy-to-power ratio) enabling them to provide services on all levels of the energy system, including generation, transmission, and distribution.[10,11] PHS (both off-river and open-loop) is a long-standing form of mechanical ES, and remains the primary, cost-efficient and reliable non-fossil flexibility option. Together with Compressed/Liquified Air Energy Storage (CAES or LAES), these mechanical ES systems will continue to provide services for the mitigation of short- and mid-term (*i.e.*, hours to days) supply deficits, including generation support and bulk storage, transmission and distribution services as well as ancillary services where high-energy and high-power capacities are required.[11,12] The main challenge for expanding the capacity of these technologies beyond techno-economics is associated with ecological and geographical constraints, as well as social acceptance limiting their use.[13]

Chemical ES technologies, such as Power-to-Hydrogen (P2Hindex: P2H\t: Power-to-Hydrogen?>), Power-to-Ammonia (P2Aindex: P2A\t: Power-to-Ammonia?>), and Power-to-Methane (P2Mindex: P2M\t: Power-to-Mehane?>), are considered promising due to their high gravimetric energy density (hydrogen $\approx$ 120 MJ kg^{-1}, ammonia $\approx$ 18.6 MJ kg^{-1}, methane $\approx$ 50 MJ kg^{-1}; lower heating values), their ability to store energy over long durations (weeks to months), and their ease of transportability[14] mainly in the Power-to-X context. Power-to-X technologies aim to convert excess renewable electricity into storable and transportable chemicals and energy carriers. Hence, besides their role in the decarbonization of the hard-to-abate industrial sectors (*e.g.*, steelmaking, chemicals) these technologies are expected to provide additional flexibility to the energy system by providing mid- to long-term ES services due to their large storage capacities, flexibility, and scalability.[15] The main key performance indicators (KPIs) hindering wide adoption of chemical ES applications can be named as high costs (both fuel production and utilization infrastructure and produced fuel cost), as well as low round-trip conversion efficiencies (20–40%).[16] Besides electricity storage, these chemical ES systems may also help to meet future demand for fuels used in heat applications, particularly as conversion technologies advance such combined heat and power engines for hydrogen. In this way, they can substitute conventional fuels in sectors where electrification is not possible or feasible.

Electrochemical ES technologies include a wide range of solid-state, flow, and semi-solid systems, categorized according to the physical state of the reactants. Within solid-state systems, Li-ion and lead-acid batteries are the most common, followed by Na-ion batteries as an emerging promising alternative.[17] Flow systems encompass several technologies such as vanadium redox-flow (VRFB), zinc–bromine and iron–chromium batteries, with VRFBs currently appearing to be most promising due to their large practical energy and power capacities. Metal-air batteries (*e.g.*, Li-air, Zn-air) represent another electrochemical alternative, although in terms of market readiness they remain among the least advanced technologies, with technological readiness levels typically in the range of 3–4. In general, batteries are considered to be less suitable for long storage durations, mainly due to self-discharge losses and economic feasibility. However, large-scale Li-ion battery ES applications are being increasingly deployed across the globe. The large-scale deployment is mainly driven by their rapid reaction



	Mechanical				Chemical			Electrochemical						Electrical		Thermal		
	PHS	CAES	LAES	Flywheel	P2H	P2A	P2M	LIB	Ni-Cd	NaS	SIB*	VRFB	LAB	SC	SMES	TCS	PCM	STES
Technology Readiness Level	9	8	7-8	9	6 - 9	6-9	6-9	9	9	8-9	6-7	7-9	9	9	5-8	5-7	6-8	6-9
Storage duration	3-6 h	1-10 h	2-24h	s-min.	h-weeks	weeks	weeks	min-6h	min-h	min-7h	< 5h	10-12 h	1-6h	s – min	ms-min	h-days	h-weeks	h-months
Efficiency (%)	70-85	> 70	45-70	85-95	20-40	n/a	n/a	85-95	60-70	75-80	> 92	68-80	75-85	90-95	90-95	40-50	~ 90	55-90
Response time	s-min	mins	mins	s	s-min	s	s	ms	ms	ms	ms	ms-s	ms	ms	5 ms	mins	mins	mins
Cycle lifetime (thousand cycles)	100-10^3	5-20	22-30	100-10^5	N/A	N/A	N/A	1.5-3.5	1-5	4-7.3	< 1.5, <10 future	> 10	0.25-2	100-10^5	10	~3.5	3 - 5	<10
Lifetime (years)	50-100	25-40	40	+20	5-30	30	30	10-20	10-25	10-20	N/A	10-25	8-20	+20	20-30	15-20	15-50	20-50
Generation Support & Bulk Storage	E, T				E			T, P, I, E	PO, T, E							E, (D), I		
Transmission Infrastructure				T				D, T						T				
Distribution Infrastructure	D				E			D, A	A, T, PtX, I							E, (D), I		
Ancillary	E, D							D, P, Ic	PO, D					E, D		E, P, (D), I		
BTM Customer Energy Management		Ic, A, D						D, P, A, I						I, D				

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

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

Technological Readiness Level (TRL)

TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

*SIBs are included in the table as an emerging technology with high deployment potential, exhibiting characteristics similar to lithium-ion batteries (LIBs). The dotted lines in energy and power capacity indicate their projected potential.

Fig. 1 Technical properties and service applications of energy storage technologies. Actors indicated in brackets indicate that service can be partly provided/benefited by the named provider/beneficiary. (Based on data adapted from ref. 10 (CC BY 4.0)).

times, high conversion efficiencies (∼90%), scalability, and declining costs, making them highly suitable for discharge durations ranging from minutes up to around 10 hours in stationary applications. They can be situated both in grid and customer energy management applications encompassing a wide range of services.[18]

Electrical ES technologies, such as Superconducting Magnetic Energy Storage (SMES) and Supercapacitors (SC), offer possibilities for transmission applications due to their quick response time (*i.e.*, milliseconds) and high power density (*i.e.*, SC = 510–3300 W kg^{-1} whereas Li-ion = 250–340 W kg^{-1}),[19] supporting maintenance of power quality.[20] Noting that SCs are considered both as an electrochemical and electrical ES technology, they are emerging for use particularly in transmission grid services where very high power density is required for very short durations. SMES proves similar technical characteristics but has a limited application for providing ancillary and customer energy management services, since the high cost associated with the cooling efforts remain a drawback.[21]

Thermal ES (TES) technologies, which are often considered among the oldest forms of energy storage, include sensible, latent, and thermochemical heat storage. They can be applied across multiple scales – from industrial processes to private end-users – for the supply of thermal loads as well electricity generation in concentrated solar power (CSP) systems. TES systems are proven to effectively store heat with efficiencies up to 90%. However, the required storage duration and characteristics of the heat source are critical factors when choosing the type of storage media and conversion path, since heat losses show a large variety based on sensible, latent and thermochemical methods. Sensible TES is widely deployed as the most conventional approach, particularly using molten salts as the storage medium in CSP plants. Latent heat storage with Phase Changing Materials (PCMs) is an increasingly promising option offering higher heat capacity and lower thermal losses. PCMs are now often applied either in combination with molten salts or as hybrid layers in CSP systems. Besides mature PCMs (salt hydrate or paraffins), many new materials and systems are under development.[19] Furthermore, these technologies offer potential for cross-sectoral ES services in a Power-to-Heat context (electricity, heating and cooling), depending on the required operational temperature range.[22]

Beyond the individual use of the different storage technologies, there is increased exploration of hybrid ES concepts, with the expectations that the limitations of one ES technology are compensated by another (*e.g.*, a combination of the extended lifespan and low cost of VRFBindex: VRFB\t: Vanadium Redox Flow Battery?> with the rapid response and high energy density of Li-ion batteries).[23] Such hybrid ES technologies might help to expand the range of services offered (*i.e.*, service stacking) *via* improved performance.[24]

In summary, ES technological choices necessitate thorough consideration of technological features and the performance of alternatives which fulfill the requirements of the services within a certain application. Hence, a single technology-centered discussion is not useful, and different storage technologies complement each other in the energy system. The brief technical overview of the ES systems provided here should serve to build the links between the technological- and application-related aspects and sustainability.

4. Sustainability assessment of energy storage

Sustainability assessments provide a critical foundation for arguments in ES decision-making. Their outcomes have the potential to influence discussions on technological advancements, investment strategies and policymaking. However, the effectiveness of sustainability assessments can only be ensured if they are conducted comprehensively and produce robust and reliable results. Despite their significance, sustainability assessments currently lack a standardized framework with clearly defined rules and assessment procedures. To some extent this is related to the individual design requirements of assessments in their specific context, which includes ES assessments. Several key principles have been developed to guide assessment processes, and ensure that assessments fulfil their role. These key principles are outlined as a guiding vision, essential considerations, adequate scope, a well-structured framework with measurable indicators, transparency, effective communication, continuity and capacity, and active stakeholder participation, which are explained briefly in the following.[25]

A guiding vision refers to a long-term strategic framework that defines overarching goals, principles and desired outcomes serving as a normative reference point, such as the UN Sustainable Development Goals, or the energy transition in the ES context. Fig. 2 presents an overview of ES technologies and their role in the energy system, linking energy supply, energy demand, and sustainability assessment approaches considering energy transition as a guiding vision.

Setting a guiding vision enables the definition of essential considerations, such as generation/demand relation, performance criteria, application requirements, available alternatives and their technical features, but also delivers transferrable inferences about economic, environmental and social system components and their interdependencies, as illustrated in Fig. 2. Furthermore, the links between the technical and sustainability spheres need to be built *via* consideration of current trends, drivers of change, risks, and uncertainties and activities which might cause cross-boundary impacts. The scope of ES sustainability assessments should describe how both short- and long-term effects of the decisions will be addressed considering spatial factors in the local and global context. Furthermore, a conceptual framework needs to be adopted or developed which incorporates and links the aforementioned aspects, which will then allow identification of indicators, data management strategy, scenario development and models. The most commonly used conceptual frameworks are Triple Bottom Line (TBL), UN Sustainability Development Goals (SDGs), Life Cycle Sustainability Assessment (LCSA), Global Reporting Initiative (GRI) Sustainability Reporting Framework, Environmental, Social and Governance (ESG) Disclosure Frameworks (*e.g.*, Sustainability Accounting Standards Boards, Integrated Reporting Framework), Sustainability Balanced Scorecard, Environmental and Social Impact Assessment (EIA/SIA) as well as Drivers-Pressure-State-Impact-Response (DPSIR).[26–32] A comparative overview of the most widely applied sustainability conceptual frameworks is provided in Table 1, highlighting their distinctive focus, scope, and application with illustrative examples in the context of energy storage systems and technologies.

The frameworks differ from one another based on the goal and scope of the assessment. For instance, LCSA quantifies impacts throughout a product's lifetime, while EIA/SIA integrate sustainability considerations into project planning, and GRI or ESG frameworks strive for strategic alignment and transparency in the corporate world. For ES sustainability assessments the conceptual frameworks should provide guidance for identifying core indicators, target values and benchmarks, as well as data management strategies including the identification of reliable data sources and collection methods. Transparency and effective communication are continuous companions of sustainability assessments for both the users of the results and affected stakeholders. The stakeholders must be involved in both assessment study development and interpretation to ensure relevant indicators are chosen to address their needs accurately.

Bearing in mind the assessment principles, one also needs to identify the values (subjective opinions, *e.g.*, strong or weak sustainability) and sustainability principles (*i.e.*, precautionary

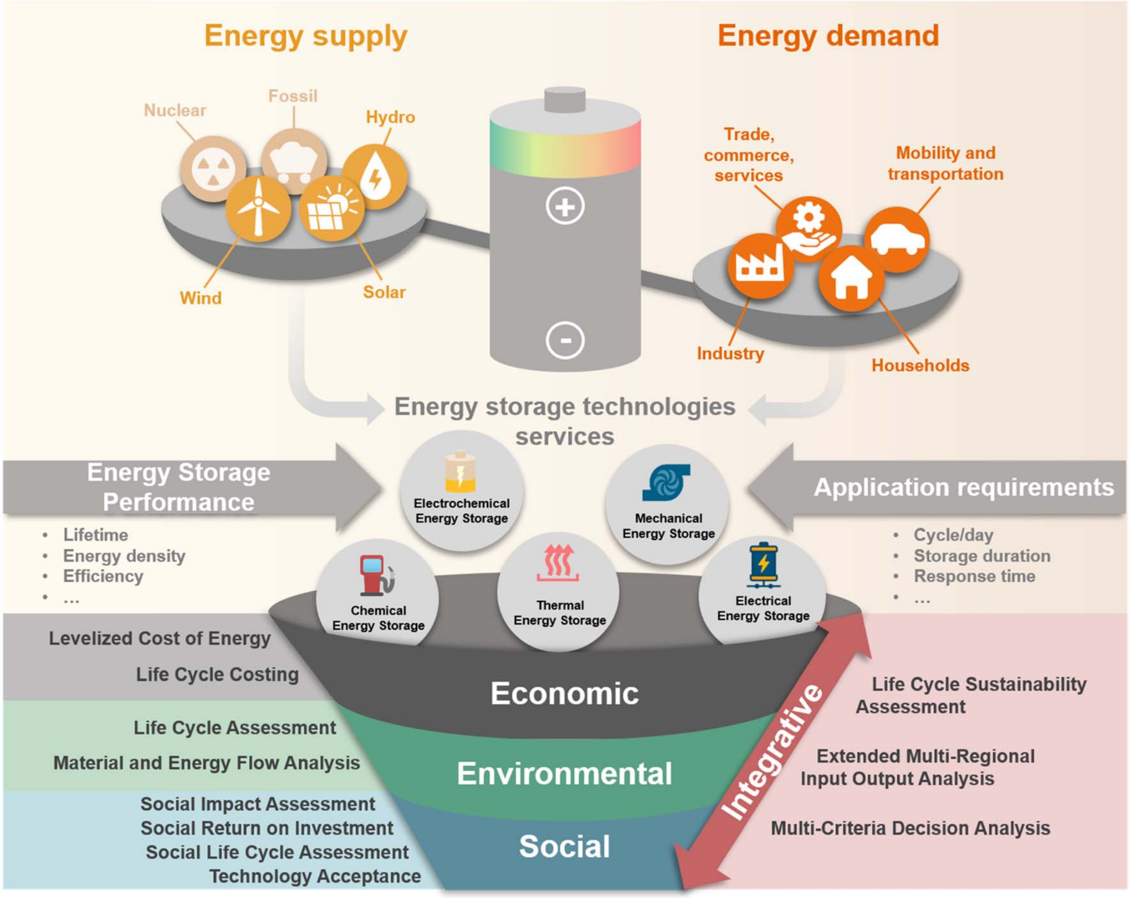


Fig. 2 Introductory figure, overview of three main sustainability assessment dimensions and corresponding method selection for ES technologies. Notice, the battery is representative for all energy storage technologies.

principle, irreversibility, regeneration, substitutability, critical loads *etc.*) for determining the approach to sustainability.[25] This then needs to be taken a step further, setting a decision context through the definition of the assessment object (*i.e.*, policies/measures, institutions, goods or services), which might influence the relevant actors, scale, complexity, uncertainties, timing, impacts and strategies majorly.

The core of a sustainability framework is methodological choice, which is influenced by the given principles, approach, and decision context. This step includes identification of suitable assessment methodologies, methods, tools, and indicators, followed by uncertainty management. Since this review focuses on assessment methods, in the following subsections the applied methods in the literature on ES sustainability are systematically reviewed considering their economic, environmental and social dimensions. 205 studies are analyzed based on their technological focus, applied assessment methods and indicators, in order to explore the current assessment landscape. A methodological comparison is provided in SI Table 1, which organizes sustainability assessment methods into economic, environmental, and social dimensions, outlining their purposes, applications, strengths, limitations, and illustrative examples in the context of energy storage systems. For the detailed overview of the collected studies, used methods, and indicators, readers are asked to refer to the SI.

4.1. Economic assessment of energy storage

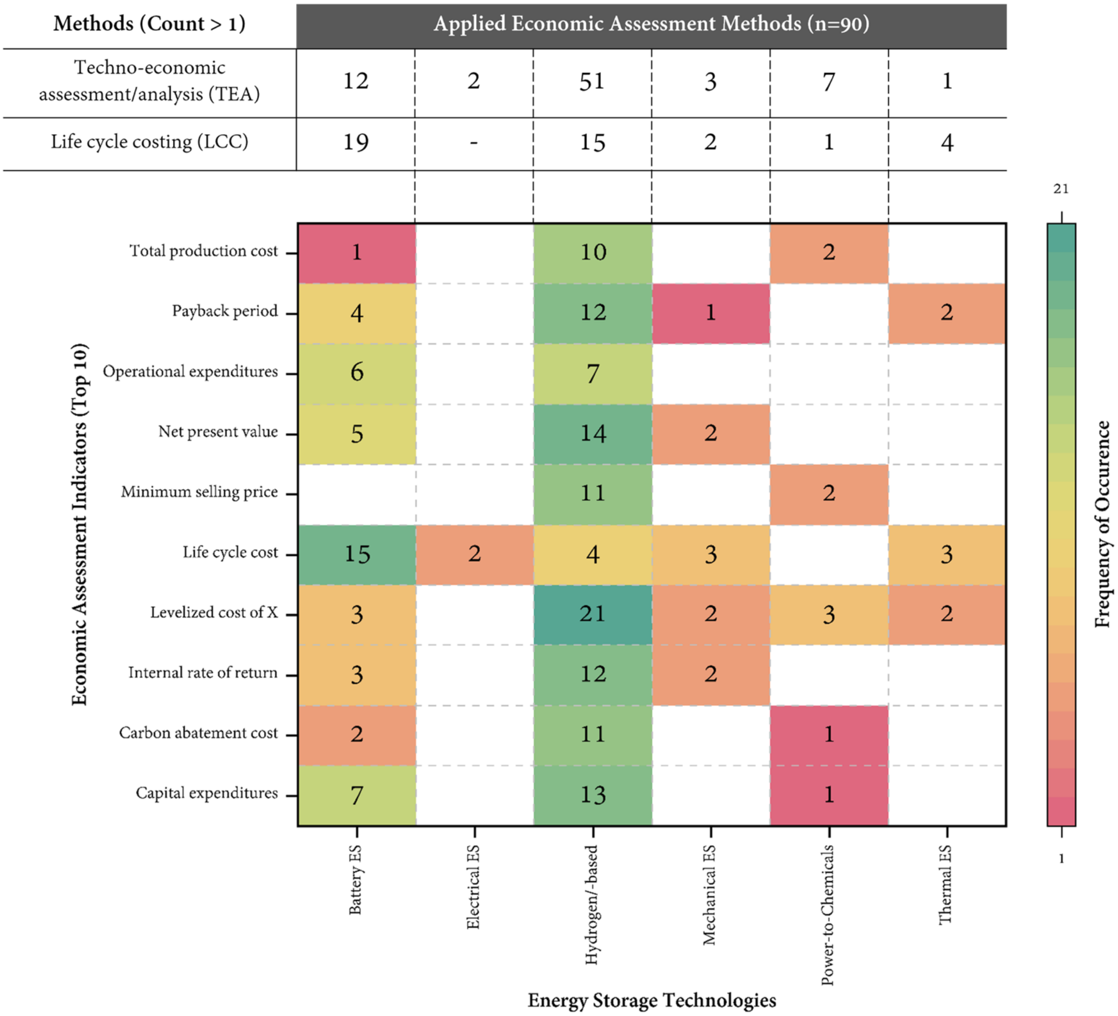
The sustainability transformation of the global energy system depends on the availability and efficient use of financial resources, which makes economics an essential pillar of sustainability. This transformation requires consideration of the internal costs of ES systems (*i.e.*, expenses directly incurred by a business, individual, process of production or consumption), but also of the external costs (costs imposed on third parties or society) to mitigate adverse sustainability impacts. Therefore, an analysis of ES economics must account for perspectives beyond profitability, considering external costs stemming from the environmental and social impacts born by other parties. Thus, it is crucial to conduct comprehensive economic assessments to provide a strong base of support for balanced decision-making which protects the interests of involved stakeholders.

Conventionally, economics has been a determinant criterion for decisions, hence an extensive literature on the economic assessment of ES systems exists, with varying levels of granularity. An overview of the collected studies is provided in Fig. 3.

Table 1 Comparison of key sustainability conceptual frameworks, highlighting their primary focus, scope, application levels, strengths, limitations, and illustrative examples in the context of energy storage systems and technologies

Framework	Primary focus	Scope & coverage	Level of application	Strengths	Limitations	ES example
TBL	Balancing economic, environmental, and social dimensions	Broad, qualitative	Organizational, project, policy	Simple, widely recognized, integrates three pillars of sustainability	Lack of standardized metrics, risk of superficial adoption ("greenwashing")	Assessing battery manufacturing firms on profitability, environmental footprint (*e.g.*, emissions), and community well-being
SDGs	Global development priorities (17 goals, 169 targets)	Global, cross-sectoral	National, organizational alignment	Provides shared global agenda, widely endorsed, measurable targets	High-level; may be difficult to operationalize at firm/project level	Linking energy storage deployment to SDG 7 (affordable and clean energy) and SDG 13 (climate action)
LCSA	Holistic evaluation across life cycle (environmental, social, economic)	Product/process oriented	Operational, project, product design	Comprehensive assessment; quantitative	Data-intensive; methodological complexity	LCA of Li-ion batteries, covering raw material extraction, production, use phase, and recycling
GRI	Standardized sustainability reporting	Broad: economic, environmental and social disclosure	Organizational (corporate reporting)	Widely adopted, enhances the transparency and comparability	Reporting burden, may encourage compliance over performance	Annual sustainability reports of battery manufacturers detailing emissions, labor conditions, and community impacts
ESG disclosure frameworks	Investor-focused sustainability performance (environmental, social, governance)	Financial materiality, risk, governance	Organizational (primarily corporate/financial markets)	Aligns sustainability with financial markets; improves investor decision-making	Narrower focus on financial materiality; less attention to broader societal impacts	ESG ratings of energy storage firms to assess investment risks (*e.g.*, supply chain governance in cobalt sourcing)
SBSC	Integrates sustainability into strategic management and performance measurement	Organizational strategy, KPIs	Organizational (strategic planning and control)	Links sustainability to business strategy; enables monitoring	Organization-centric; may overlook broader systemic issues	Incorporating environmental KPIs into performance dashboards of grid-scale storage companies
EIA/SIA	Anticipating and mitigating environmental and social impacts of projects	Project-specific	Project, infrastructure, development planning	Legally mandated in many jurisdictions; preventive approach	Often reactive; scope may exclude long-term or cumulative impacts	EIA/SIA for constructing large-scale battery storage facilities assessing land use, emissions, and community acceptance
DPSIR	Causal framework for analyzing environmental and socio-economic interactions	Environmental systems focus	Policy and research (macro level)	Useful for system-level analysis; policy-relevant	Complexity; limited attention to economic/organizational decision-making	Modeling how demand for storage (driver) creates pressures on mining, alters environmental states, and elicits regulatory responses

Bearing in mind the search string used to identify relevant studies, 14 were identified which solely apply economic assessments in the sustainability context, but this number increased to 90 when including studies which apply economic assessments in combination with other methods, or as parallel assessments. The heatmap provided in Fig. 3 shows the utilized economic indicators and assessment methods per ES technology, noting that an individual study may include multiple indicators, technologies and assessment methods. As can be observed, the vast majority of the collected studies focus on hydrogen and hydrogen-based renewable fuels, as well as



Methods (Count > 1)	Battery ES	Electrical ES	Hydrogen/-based	Mechanical ES	Power-to-Chemicals	Thermal ES
	Applied Economic Assessment Methods (n=90)					
Techno-economic assessment/analysis (TEA)	12	2	51	3	7	1
Life cycle costing (LCC)	19	-	15	2	1	4

Economic Assessment Indicators (Top 10)	Battery ES	Electrical ES	Hydrogen/-based	Mechanical ES	Power-to-Chemicals	Thermal ES
Total production cost	1		10		2	
Payback period	4		12	1		2
Operational expenditures	6		7			
Net present value	5		14	2		
Minimum selling price			11		2	
Life cycle cost	15	2	4	3		3
Levelized cost of X	3		21	2	3	2
Internal rate of return	3		12	2		
Carbon abatement cost	2		11		1	
Capital expenditures	7		13		1	

Fig. 3 Applied economic assessment methods ($n = 90$) across various energy storage technologies. The heatmap presents the frequency of occurrence of the top 10 most frequently used economic assessment indicators for different energy storage technologies. The color gradient represents the frequency of occurrence, with green indicating higher frequency and red indicating lower frequency. Note that an individual study may include multiple indicators, technologies and assessment methods.

batteries. It can thus be seen that these areas dominate in line with current technological developments.

The methodological approaches in the reviewed assessments predominantly employ Techno-economic Assessment/Analysis (TEA) and Life Cycle Costing (LCC) methods. The main reasons for this preference include ease of application, straightforward assessment procedures, data availability, the existence of supporting tools, and relatively low time requirements. However, the extent to which these advantages hold is largely determined by the depth of analysis undertaken in the study. TEA is not a standardized method, and multiple approaches exist. Techno-economic feasibility is often assessed using engineering cost estimation and analogy-based approaches, with a focus on Capital Expenditure (CAPEX) and Operational Expenditures (OPEX). CAPEX typically encompasses direct, indirect, fixed, and working capital costs, while OPEX covers fixed and variable costs, including power- and energy-capacity-related operation and maintenance (O&M) expenses.[19] Estimating CAPEX and OPEX is essential for understanding the cost structure of ES systems and must be contextualized with respect to technological specifications and application requirements. These steps are frequently the most time-consuming and data-intensive, owing to incomplete information, limited vendor input, or a lack of application-specific data. Given the importance of CAPEX and OPEX, the economic model must accurately capture the relationship between technological performance and operational parameters.

Hence, as shown in Fig. 3, Levelized Cost of X (LCOX) is the most frequently used indicator which incorporates the aforementioned aspects in TEAs to analyze overall cost per unit of energy delivered over lifetime (*e.g.*, levelized cost of electricity, levelized cost of hydrogen, levelized cost of heat) in aggregated terms. It allows comparisons and benchmarking of technologies under identical operational conditions and/or application based on the same energy vector.[33] Classically, TEAs use the levelized cost approach with a strong focus on internal costs, excluding internalization of the external costs.

Due to the increasing prominence of climate change, some studies incorporate costs like greenhouse gas (GHG) emissions and carbon abatement cost (see Fig. 3). Considering the studies identified, indicators that account for external costs remain underutilized. This is particularly so for external environmental and social costs. Furthermore, a key observation is the insufficient focus on the end-of-life (EoL) phase when considering life cycle stages. In most cases, this phase is limited to dismantling and disposal, and often overlooks the impacts of recycling raw materials.

Additionally, a set of studies use classic dynamic investment calculation-based indicators such as Net Present Value (NPV) ($n = 21$), annuity, and Internal Rate of Return (IRR) ($n = 17$) in static or dynamic models to aggregate those parameters over the system's lifetime considering the time value of money. Payback Period (PBP) is another indicator that is widely considered for hydrogen/hydrogen-based renewable fuels since the CAPEX required for the fuel production, supply, and utilization infrastructure requires high initial investment costs. Moreover, Minimum Selling Price (MSP) and Total Production Cost (TPC) are frequently used in assessments of hydrogen/hydrogen-based renewable fuels. Such indicators are often selected for specific technologies because they provide a convenient basis for comparison and benchmarking within the same category. However, this approach limits comparability with other types of technologies that may provide similar services (see Fig. 3). Hydrogen-based fuels are also generally regarded as expensive alternatives under current fuel price benchmarks. Hence MSP and TPC are also applied for comparison with fossil-based options. Nevertheless, as these indicators do not capture the downstream utilization of such fuels, they offer only limited comparability, for instance in the decision-making context when used as the only economic KPI.

LCC is identified as the second most widely-applied approach for economic assessments, predominantly applied to batteries and hydrogen/-based ES. This is likely due to the rapid emergence of these technologies and the significance of their lifecycle stages. Moreover, LCC is often preferred due to its practicality in leveraging Life Cycle Assessment (LCA) models. LCC refers to the total cost of ownership (TCO), by including costs from raw materials or acquisition to EoL. Generally, it is widely used for estimating the total cost of a system, product, service or infrastructure for decision-making on long-term investments. Although it shares similarities with TEA, its distinct feature lies in the more detailed integration of life cycle thinking. Unlike levelized cost, LCC incorporates the ideal costs of each life cycle stage, including replacements, disposal and recycling.

Among the considered studies, LCC is commonly applied to batteries since the life cycle-oriented approach allows the incorporation of costs associated with raw materials and manufacturing, but also incorporates technical performance criteria such as capacity fade, cycle degradation and system lifespan for the use phase. Under identical operational conditions, LCC enables a fair comparison of different batteries to assist decisions in technological choices. Furthermore, variations of LCC, such as environmental LCC (E-LCC), full environmental LCC (FE-LCC), and societal LCC (S-LCC), internalize environmental and social costs using monetization to approximate the actual total cost.[34] However, these variations of LCC are not applied very frequently within the collected studies in the ES context. These variations are useful for capturing the full spectrum of actual costs. However, they require a more complex approach, since monetary valuation relies on detailed life cycle inventory data, and many environmental and social impacts lack standardized high quality or region-specific datasets. The lack of universally agreed monetization frameworks also makes the results less comparable and sometimes disputed.

Other, less frequently used methods are Socio-economic Assessment (SEA) including fiscal analysis, Input/Output Method (or Multi-regional Input-Output MRIO), cost-benefit analysis, and risk-benefit analysis. These evaluate the economic feasibility and societal benefits of ES projects considering different perspectives (manufacturer, customer or society).[35] However, none of these methods were captured in the literature search for ES systems. These methods are often not employed because most studies adopt a sector-oriented perspective rather than product- or service-specific micro-level assessments. The prevailing motivation is typically case-specific feasibility in the collected studies, rather than evaluating cumulative sectoral impacts.

Considering the methods presented here, it is evident that the necessary methods to thoroughly analyze the economics of ES systems exist and are well-developed, if not utilized to their full extent. Based on the observations derived from the analysis, the following general and specific recommendations are made to enhance economic assessments of ES systems:

(i) *Granularity*: enhance the level of detail and granularity in economic assessments by improving data quality and availability, while balancing this against practical constraints such as time and resource expenditure.

The value of higher-resolution input data has been shown in studies of battery ES in power markets, where revenue and cost outcomes differed substantially when individual services such as frequency regulation, reserve capacity, and voltage support were considered separately.[36] Similarly, research on vehicle-to-grid applications has demonstrated that using real-world duty cycle data revealed degradation and economic values which were not captured by aggregated profiles.[37]

(ii) *Case specific considerations*: selection of assessment methods that enable incorporation of economic aspects related to the specific market region, regulatory framework, and ownership model of the ES project, as these significantly influence feasibility and interdependent sustainability aspects.

For example, LCC of thermal ES systems showed that economic feasibility depends strongly on regional market rules and service remuneration schemes.[38] Similarly, hybrid battery–fuel-cell system assessments highlighted the role of local policy and ownership structures in shaping outcomes.[39] The decarbonization of shipping through alternative fuels further illustrates how regulatory frameworks, such as the IMO's emission targets, directly condition economic feasibility.[40]

(iii) *Cost data*: address the challenge of data transparency and representativeness by supporting the development of standardized, open-access cost databases tailored to various ES technologies and deployment contexts.

Limitations in available cost data often lead to boundary exclusions, such as the omission of EoL phases in hybrid energy storage studies.[41] Ex-ante assessments of lithium-ion battery recycling similarly noted that assumptions about process parameters critically influence economic outcomes, underscoring the need for standardized and transparent datasets.[42] Moreover, environmental life cycle costing of hydrogen systems has shown the benefits of using harmonized price datasets to monetize externalities consistently across studies.[43]

(iv) *Use phase*: clear definition of the application context (*e.g.*, mobility, grid balancing, residential) and services provided (*e.g.*, frequency regulation, peak shaving), to ensure comparability and relevance of cost assessments across studies.

Studies that specify service portfolios, such as frequency regulation, peak shaving, and reserve provision, provide results that are more comparable and relevant for decision-making.[36,38] For hydrogen systems in off-grid contexts, explicit definitions of long-term storage and load-balancing services further demonstrate the importance of contextual clarity.[44] In the mobility sector, research on vehicle-to-grid integration shows how explicitly defining bidirectional charging services leads to more accurate assessments of both costs and revenues.[37]

(v) *Role of economics in the sustainability context*: The economic aspects of ES systems play a crucial role in enabling the energy transition. Therefore, consideration of economics beyond conventional techno-economic feasibility is of great importance. The current narrow scope of assessments should be expanded toward internalization of the external costs (both social and environmental), observing the interdependencies. While doing so, life cycle thinking might be employed as a guiding vision for embracing the entire supply chain, particularly with the inclusion of EoL phases. Use of LCC and its variants leveraging the LCAs might be useful.

This broader perspective is evident in the development of indicators that link costs with resource depletion through LCC.[45] E-LCC of hydrogen systems has similarly demonstrated how monetization of externalities changes economic outcomes.[43] Integrated cradle-to-grave assessments of electric buses also show the value of combining cost and environmental metrics to reveal trade-offs and support sustainable decision-making.[46] Ex-ante assessments of lithium-ion battery recycling further illustrate how EoL management significantly alters both cost and impact outcomes.[42]

(vi) *Framework requirements*: encourage the standardization of economic assessment frameworks, including the use of consistent indicators, functional units, and cost definitions, to improve comparability and decision relevance across studies.

Reviews of techno-economic assessments of storage systems have repeatedly noted inconsistencies in system boundaries, functional units, and cost definitions, which limit comparability.[47] The introduction of formalized indicators such as the Commodity Life Cycle Costing Indicator has been suggested to address these issues.[45]

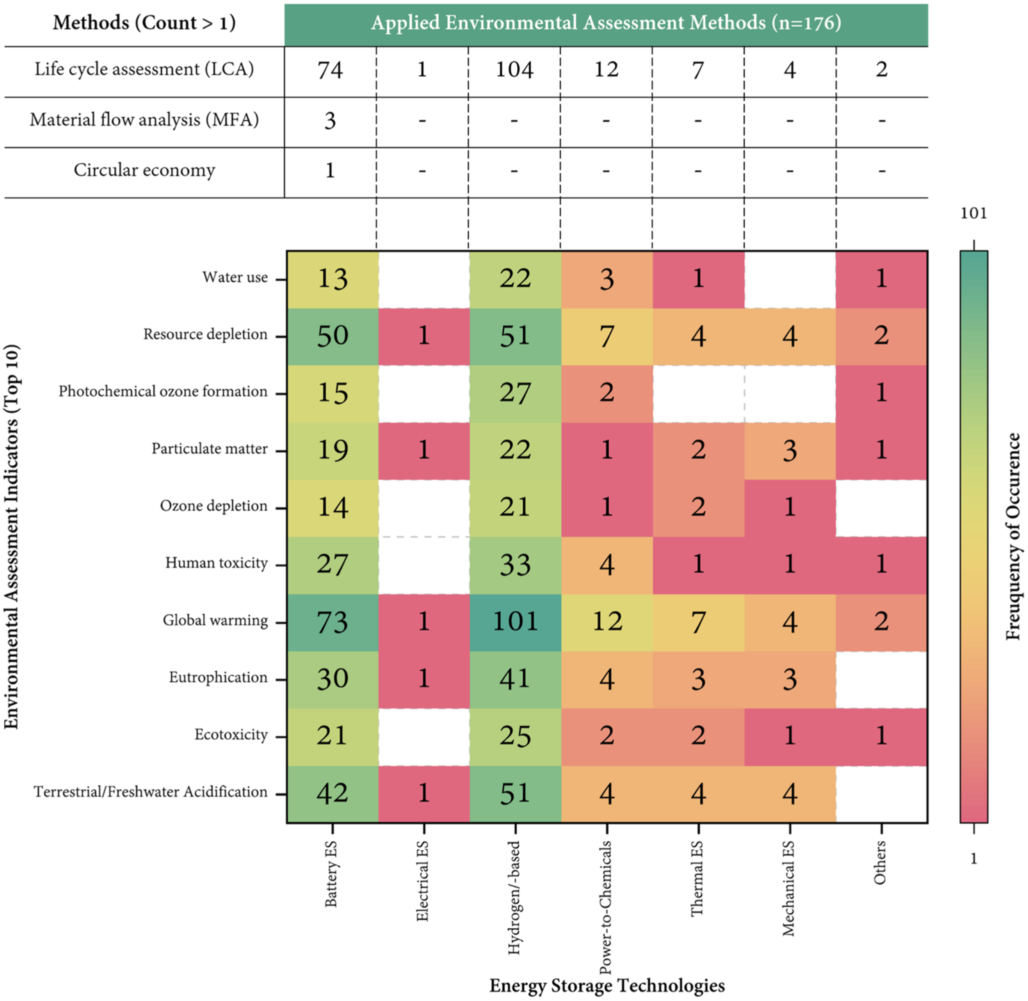
Remarkably, among the collected studies, the number addressing these recommendations is increasing. However, in order to embrace sustainability as a whole it is evident that more effort is required to improve the quality of the assessment to incorporate the points above and enhance their effective utilization in decision-making practices.

4.2. Environmental assessment of energy storage

Environmental sustainability is a crucial pillar of sustainability transformation of the global energy system, driven by the growing concerns over breached planetary boundaries.[48] As introduced previously, ES systems provide features proving the capability to offer diverse services for promoting the deployment of renewables. But ES systems also impose environmental burdens throughout their life cycle, from raw material extraction and manufacturing to usage and EoL management. The growing demand for ES systems, and increasing concerns about their environmental impacts, are driving the momentum for ex-ante and ex-post environmental assessments. The scope of environmental assessments shows varying intensity in terms of considered system boundaries, which is driven by the identified hotspots which hinder their adoption for specific applications, as explained in the technology overview section.

Notably, in all studies ($n = 176$) assessing the environmental aspects of ES systems, LCA is used as the primary method. LCA is a well-known and standardized methodology for evaluating environmental impacts across all life cycle stages as defined in ISO 14040 standards.[49,50] It consists of four iterative steps: the goal and scope definition, Life Cycle Inventory (LCI) analysis, Lifecycle Impact Assessment (LCIA), and interpretation.[51] A comprehensive understanding of the value chain focusing on material and energy flows between technosphere and ecosphere is essential for conducting an LCA. There are two LCA types; attributional and consequential LCAs differ in purpose, system boundaries, and assumptions about indirect impacts. Attributional LCA evaluates the environmental impacts of a product or system at a given point in time. Whereas consequential LCA analyzes the environmental impacts of changes in production and consumption, modelling how a decision or policy influences the environmental performance of a product, process, system or service. In the ES context, the vast majority of LCA studies apply attributional LCAs, whereas consequential LCAs to evaluate the global impacts of ES technologies have not been researched on a large scale.[52] As in the economic dimension, batteries and hydrogen-based fuels dominate the collected environmental assessment studies, as illustrated in Fig. 4. Noting that individual studies might consider more than one technology, method or indicator. Considering the availability of diverse environmental impact assessment methods, indicators here are unified for simplicity, referring to their midpoint equivalent in CML-IA impact assessment, since the statistical analysis aims to identify the hotspots in the considered areas of protection.

Mostly, LCAs are conducted as parallel or integrated assessments in the considered studies, together with economics. In some cases, LCAs are supplemented with other



Methods (Count > 1)	Applied Environmental Assessment Methods (n=176)						
Life cycle assessment (LCA)	74	1	104	12	7	4	2
Material flow analysis (MFA)	3	-	-	-	-	-	-
Circular economy	1	-	-	-	-	-	-

Environmental Assessment Indicators (Top 10)	Battery ES	Electrical ES	Hydrogen/-based	Power-to-Chemicals	Thermal ES	Mechanical ES	Others
Water use	13		22	3	1		1
Resource depletion	50	1	51	7	4	4	2
Photochemical ozone formation	15		27	2			1
Particulate matter	19	1	22	1	2	3	1
Ozone depletion	14		21	1	2	1	
Human toxicity	27		33	4	1	1	1
Global warming	73	1	101	12	7	4	2
Eutrophication	30	1	41	4	3	3	
Ecotoxicity	21		25	2	2	1	1
Terrestrial/Freshwater Acidification	42	1	51	4	4	4	

Fig. 4 Applied environmental assessment methods ($n = 176$) across various energy storage technologies. The heat map presents the frequency of occurrence of the top 10 most frequently used environmental assessment indicators for different energy storage technologies. The color gradient represents the frequency of occurrence, with green indicating higher frequency and red indicating lower frequency. Note that an individual study may include multiple indicators, technologies and assessment methods.

assessment methods to overcome the shortcomings of the method or to improve the comprehensive evaluation of ES systems, as elaborated in the following.

Hydrogen and hydrogen-based fuels such as ammonia, syngas, e-fuels, and methane are the most prominent technologies assessed ($n = 104$) in the selected LCA studies. Their focus is mainly on global warming, resource depletion, eutrophication and terrestrial/freshwater acidification impact categories as illustrated in Fig. 4. Herein, the system boundaries are often limited to fuel production *via* renewables, excluding transportation, storage, and downstream use of the produced energy carriers. Omitting certain life cycle stages or defining narrow system boundaries often limits the interpretation of the assessment results as well as the value to informed decision-making.

As for batteries, a significant share of the collected studies focusses on Li-ion batteries ($n = 55/74$) due to their enabling role in mobile and stationary applications. Key impact categories considered are global warming, resource depletion, terrestrial/freshwater acidification, and eutrophication. Li-ion batteries can have high environmental impacts showing variations based on different chemistries (*e.g.*, Nickel Manganese Cobalt (NMC) or Lithium Iron Phosphate (LFP) chemistries) due to their high material and energy intensity considering material supply-chain and manufacturing phases, as well as limited EoL treatment strategies. To address these challenges, the EU Battery Directive establishes regional regulatory measures aimed at reducing the environmental burdens caused by batteries.[53] This directive mandates sustainability assessments aiming to reinforce advanced recycling strategies, improve resource efficiency, and integrate greener battery chemistries. Besides studies considering the cradle-to-gate and cradle-to-grave impact of batteries, eight studies focus on open- and closed-loop recycling strategies for holistic consideration of environmental impacts, where open-loop recycling refers to the reprocessing of materials into products of different quality or function, and closed-loop recycling returns materials into the same product system with minimal quality loss.[42,54–60]

Beyond LCA, several other methods can be applied to evaluate the environmental impacts of ES systems, either independently or in combination with LCAs. These include Material Flow Analysis (MFA), Hybrid Multi-Regional Input–Output (hMRIO) LCA, Criticality Assessment and Circular Economy (CE) approaches. Although not equally widespread, such methods can complement LCAs by providing additional insights into resource efficiency, material criticality, and broader environmental implications. Their relevance is also technology-dependent, as well as the goal and scope of the assessment. For example, MFA is particularly useful in the context of batteries due to their reliance on critical raw materials, while it is less directly applicable to hydrogen-based systems.

Dynamic and probabilistic MFA models examine the physical interactions of systems primarily focusing on mass flows but can also incorporate energy flows.[61] This is considered to be a good base for LCI development and assessment of environmental impacts. Two of the identified studies apply MFA in combination with LCAs, addressing global warming impacts. One examines Li-ion, Li-air, and Na-ion batteries, while the other considers Li-ion batteries, scrutinizing the impacts associated with raw material supply, manufacturing, and EoL recycling.[54,56] In another study, LCA, CE and Substance Flow Analysis (SFA) methods are applied jointly, providing a complete environmental analysis of Lead-acid batteries in the context of resource efficiency and EoL treatment benefits.[55] While SFA, as a more specific form of MFA, focuses on tracking the flow of a particular substance (*e.g.*, lead), MFA in general covers materials more broadly, allowing for a systemic view of stocks and flows. As such, the application of MFA, or SFA as its specific form, improves the quality of the assessment by enabling a more detailed consideration of material-related aspects.

Furthermore, the concept of CE is increasingly being operationalized in a contextualized and nuanced manner.[62] The methodological shortcomings in detailed incorporation of recycling and circularity into environmental assessment have led to the emergence of CE as a unique field of research.[63] As such, the perception towards CE is expanded *via* incorporation of the sustainability impacts of circularity, as in the case of impact assessment method development for LCAs.[64] Not being so prevalent, four literature studies are identified in the collected studies which integrate the CE approach into LCAs. One study introduces a material circularity indicator into LCA to inform circularity strategies of alkaline batteries.[65] An infinite LCA model is presented in another study using circularity to evaluate resource efficiency and environmental impacts with the aid of MFA.[55] Another example employs a CE approach in their LCA study to assess the environmental impacts of electric vehicle batteries.[57] Furthermore, the fourth study introduced the eco-design wheel concept to improve the life cycle environmental performance of proton-exchange membrane fuel cells, focusing on critical materials recycling.[66] The integration of CE indicators can potentially provide broader insights into improved sustainability to support the regeneration of ecosystems, the minimization of waste and pollution, and the extended use of products and materials, all depending on the specific goals and scope of the assessment. Each provides distinct insights; LCA captures environmental impacts across life cycle stages, MFA highlights material stock and flows as well as potential resource bottlenecks, and CE indicators focus on resource circularity and efficiency. While all methods can inform decisions, their results are shaped by differing system boundaries, assumptions, and data requirements. This limits direct comparability and challenges the integration of their indicators into a unified KPI framework. Instead, this approach should be seen as complementary, offering different mutually reinforcing perspectives on the sustainability of ES technologies. Their combined use can provide a more holistic understanding, though care must be taken when interpreting or aggregating the results across methods.

The hMRIO is another method that can be applied for environmental assessment of ES systems. It is derived from input–output analysis and offers a detailed view of sectorial interdependencies that are incorporated into LCI development.[67] However, hMRIO and its extensions suffer from aggregated process representations. Thus, hybrid approaches have been proposed to overcome the limitations of LCA and MRIO by considering detailed value chains and avoiding system boundary limitations.[68,69] These approaches aim to improve assessment precision by incorporating technological representativeness and comprehensive value chain considerations, but are not yet widely applied in the field of ES. Among the reviewed studies, one uses this method to focus on the global warming potential of fossil-derived hydrogen for mobility applications.[70]

Last but not least, criticality assessments evaluate the vulnerability caused by the supply of energy sources or minerals on the economy, considering indicators of scarcity, rarity, criticality, and resource depletion.[71] This review does not consider risk-related assessments; hence, the search string did not return any criticality assessment based on defined attributes. However, these assessments can be considered highly relevant for economic and environmental assessments. For economic assessments, supply chain-related aspects are relevant in terms of import reliance and supply risk, while for environmental assessments the implications can be extended towards resource use and their impact on various categories in LCA studies.[72] To the authors' best knowledge, several studies exist which evaluate criticality alongside environmental impacts using LCA for batteries.[73–75] Unlike other methods, criticality assessments (which can vary strongly) also consider supply risk attributes, including geopolitical factors *via* methods such as ESSENZ for material intensive ES technologies.[76]

Based on the methodological overview and reviewed studies, the following recommendations are made to draw attention to important aspects when conducting environmental assessments of ES systems, which might also be applicable for assessments conducted in other impact dimensions:

(i) *Goal & scope definition*: establish a well-articulated goal and scope that reflects the intended application, function of the assessment object, and stakeholder needs, as these foundational elements shape the entire assessment process.

On goal and scope definition, the general principles outlined in ISO 14040 standards apply for LCAs and can also inform environmental assessment methods that currently lack formal standardization.[49,50] These principles emphasize transparency, clarity of purpose, and relevance to the decision context, and thus provide useful guidance for setting the fundaments of any assessment study. In practice, this means that critical points such as the intended application, the defined system function, the assumptions underpinning scenarios, and the stakeholders' needs should be explicitly articulated from the outset. Clear goal and scope definitions not only shape boundary choices and functional units but also determine whether the study outcomes will be robust and decision-relevant. As part of this step, the choice of a functional unit must be consistent with the defined system function and intended application, since it provides the reference basis for comparability across technologies.

- *Functional unit*: use representative functional units (*e.g.*, kg CO_2-eq per converted kWh) and allocation approaches that reflect the full range of services and value streams provided by the ES technology.

The choice of functional unit must be consistent with the criteria defined in the goal and scope of the assessment, ensuring comparability with alternative technologies. When the study is comparative, a harmonized and transparent functional unit (*e.g.*, per kWh delivered, per kilometer travelled) is essential for fair evaluation. If the study is not conducted comparatively, the reported results should still be expressed in a way that ensures reproducibility and allows subsequent use of the outcomes in broader assessments or meta-analyses.

- *System boundaries*: provide a comprehensive definition of system boundaries to include all relevant life cycle stages including mining, material processing, manufacturing, use, and EoL, ensuring the environmental impacts are neither underestimated nor shifted between stages.

A common shortcoming in environmental assessments of ES technologies is the inconsistent treatment of life cycle phases: many studies stop at manufacturing ("cradle-to-gate"), omit use-phase efficiency losses, or neglect EoL processes. These omissions can distort outcomes, for instance ignoring raw material extraction underestimates the upstream burden of batteries, while neglecting recycling overlooks potential credits from material recovery. A useful analogy is the distinction between Scope 1, 2 and 3 GHG emissions: Scope 1 (direct emissions during operation), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other upstream and downstream activities, including raw material supply and disposal). Just as comprehensive GHG accounting requires all three scopes, robust LCA of ES systems should, where feasible, adopt cradle-to-grave or cradle-to-cradle boundaries to ensure completeness and comparability across studies.

- *Material-related add-ons*: incorporate circularity and resource criticality perspectives in the evaluation of the EoL phase to provide a more holistic view of long-term environmental implications.

As highlighted in (*v*), combining complementary methods can enhance the interpretation of results and provide stronger arguments for decision-making. In particular, incorporating aspects such as circularity and resource criticality has become increasingly important. These perspectives, especially when applied to EoL phases, can significantly influence the overall sustainability profile of ES technologies. Accounting for recycling, reuse, material scarcity, or critical raw material dependence not only enriches conventional LCA and LCC results but also strengthens their relevance for long-term policy and investment decisions.

(ii) *Role of stakeholders*: preliminary research needs to identify relevant stakeholders and create a map if possible.

Increasingly, co-construction approaches are being applied in LCAs, where stakeholders are actively involved from the study design phase onward. This participatory process helps to define the goal and scope, based on a consensus of what outcomes, presented in which form, will be most useful for generating knowledge to inform real-world decisions. Early involvement ensures that the chosen system boundaries, functional units, and indicators reflect stakeholder priorities, increases transparency, and enhances the credibility and uptake of results.

(iii) *Data management*: use primary (measurement-based) data where possible. If secondary data is used, its coherence, quality, and reliability should be assessed, and experts should be consulted when adjustments are needed to ensure sound assumptions.

For example, measured data on cycling, round-trip efficiency, and ageing under real-world duty profiles provide far more accurate inputs for LCAs and LCCs than generic database values. Conversely, reliance on outdated or regionally mismatched secondary datasets (*e.g.*, global averages for battery production, or assumed constant efficiencies) can misrepresent results and lead to incorrect conclusions about a technology's competitiveness. Where measurement is not feasible, uncertainty analysis and sensitivity testing should accompany the use of secondary data to ensure that decision-relevant insights remain robust.

(iv) *Supplementary method use*: mitigate the limitations posed by data scarcity and time constraints by integrating methods such as MFA and CE approaches, which help to capture comprehensive material flows and life cycle closure.

The use of complementary methods can improve the robustness of assessments, particularly where the technological scope is broad and decision-relevant results require greater comprehensiveness. It is therefore recommended to consider the integration of supplementary methods to capture additional dimensions of sustainability and provide stronger decision support. At the same time, consistency and harmonization of the chosen methods are essential to ensure that the results remain coherent, transparent, and comparable across studies.

(v) *Use phase*: recognize that the use phase is often the most impactful and varies significantly by application. Misinterpretations can arise in comparative studies without proper functional alignment (*e.g.*, high-power *vs.* high-energy systems).

As noted previously in the context of economic assessments, the use phase can strongly influence overall results in environmental assessments of ES technologies. For example, cradle-to-gate impacts of a given technology may appear higher than competing alternatives, but superior performance during the use phase (*e.g.*, higher efficiency, longer lifetime, or provision of multiple services) can ultimately lead to better environmental outcomes. This underscores the importance of explicitly modelling the use phase with robust, context-specific data. Bound to the points raised in (iii) data management, careful treatment of use-phase impacts is crucial for drawing reliable conclusions about the overall environmental sustainability of energy storage technologies.

(vi) *Sensitivity and uncertainty management*: include sensitivity and uncertainty analyses to test the robustness of assumptions and outcomes, especially in studies that inform policy or investment decisions.

Sensitivity and uncertainty management provides perspectives that go beyond the base-case results, enabling an understanding of how outcomes change under different parameter variations. Such analyses help to identify break-even points and clarify which technological, operational, or contextual changes could enable (or hinder) improved sustainability performance. By elaborating results with sensitivity tests and uncertainty analyses, studies can strengthen their interpretive power, highlight key interdependencies, and provide more robust guidance for policy and investment decisions.

(vii) *Dynamic methods*: promote the use of Prospective Life Cycle Assessment (pLCA) and other forward-looking methods to address the evolving nature of ES technologies and deployment scenarios.

The use of dynamic methods can bring a more forward-looking perspective into assessment results, particularly for prospective studies, as in the examples in the collected studies on batteries and hydrogen.[54,77] Most LCAs still rely on static and often outdated background and foreground datasets, which can deviate significantly from anticipated future developments when assessing immature technologies. Assessments can better reflect technological progress by adopting dynamic modelling approaches such as pLCA, scenario analysis, or time-dependent inventory considering evolving energy mixes and expected changes in supply chains. This enhances the relevance of the results for long-term decision-making and policy support.

4.3. Social assessments of energy storage

The demand for social assessments is increasing due to multi-faceted social challenges such as equity, justice, human well-being, participation and cultural integrity, which arise from technological developments and also applies to ES systems.[78–80] Emerging efforts to address the social foundation in the sustainability context often lag behind economic and environmental concerns. The social foundation encompasses various aspects related to human wellbeing, such as food, health, education, income, work, peace, justice, political voice, social equity, gender equity, housing and networks.[81] The social impacts of ES systems vary significantly depending on the technology and geographical context, with particular attention given to the material supply chain and manufacturing processes. Unveiling social aspects reveals an additional layer of complexity, as social considerations are often intangible, subjective, dynamic, and culturally dependent, thus hardly allowing a stable and generalized problem statement.[82] Hence, the social impact assessment of ES systems remains less examined compared to other sustainability dimensions, as reflected by the literature review, where 17 relevant studies were identified. These ES social assessment studies rely solely on the Social Life Cycle Assessment (S-LCA) method as presented in Fig. 5. Additionally, studies retrieved by the search string that do not directly address social aspects in the ES context were grouped under 'others' and 'power-to-chemicals'. These include, for example, a protocol for defining supply chains in product S-LCA, or studies on methanol production as a chemical feedstock.

S-LCA was developed based on the life cycle thinking framework, and shares a similar modelling approach to LCA. Its widespread adoption in social impact assessments has been influenced by advancements in LCA, as well as the method's practicality and its ability to extend impact dimensions to social aspects by leveraging modelled elementary flows, products, and processes. The S-LCA assessment procedure has recently been standardized and is structured similarly to LCA standards, as defined under ISO 14075:2024.[83] The standardization complements the UNEP 2020 Guidelines for S-LCA and Methodological Sheets which served previously as the main reference for practitioners.[84] S-LCA covers various impact subcategories such as human rights, working conditions, health and safety, and cultural and social wellbeing, as well as stakeholder categories of governance considering workers, local communities, consumers, society, and value chain actors. S-LCA assessments in the ES field mainly address social risks in raw material extraction, the global supply chain, and labor conditions in the manufacture of ES technologies within cradle-to-gate system boundaries.[85] But beyond that, S-LCA is also utilized to assess the effects of ES on local communities, considering both negative impacts (land use, displacement or community health and safety) and potential positive impacts (job creation, local economic development). S-LCA can be used to scrutinize ethical and governance issues under corporate social responsibility (CSR) for anti-corruption practices, and transparency purposes under the value chain actor stakeholder category. Despite a small sample size, the literature analysis points out the focus on batteries (particularly Li-ion batteries) and hydrogen/-based fuels. The considered studies on battery technologies primarily focus on assessing social risks and impacts across various stages of the battery life cycle, including raw material extraction, production, manufacturing, supply chain activities, and EoL processes.[86,87] Li-ion batteries (particularly LFP-type) is frequently analyzed, with specific attention to supply chains in regions such as China, Japan, South Korea, Finland, and Germany.[88] Key aspects include the evaluation of social risks associated with mining practices (*e.g.*, switch-on switch-off mining), the influence of mineral price volatility on social hotspots, and the development of S-LCA frameworks to systematically assess stakeholder-related impacts.[89–91] Additionally, some studies explore the broader social implications of mobility services linked to battery technologies.[92] For hydrogen, one of the conducted studies proposes practices to integrate S-LCA

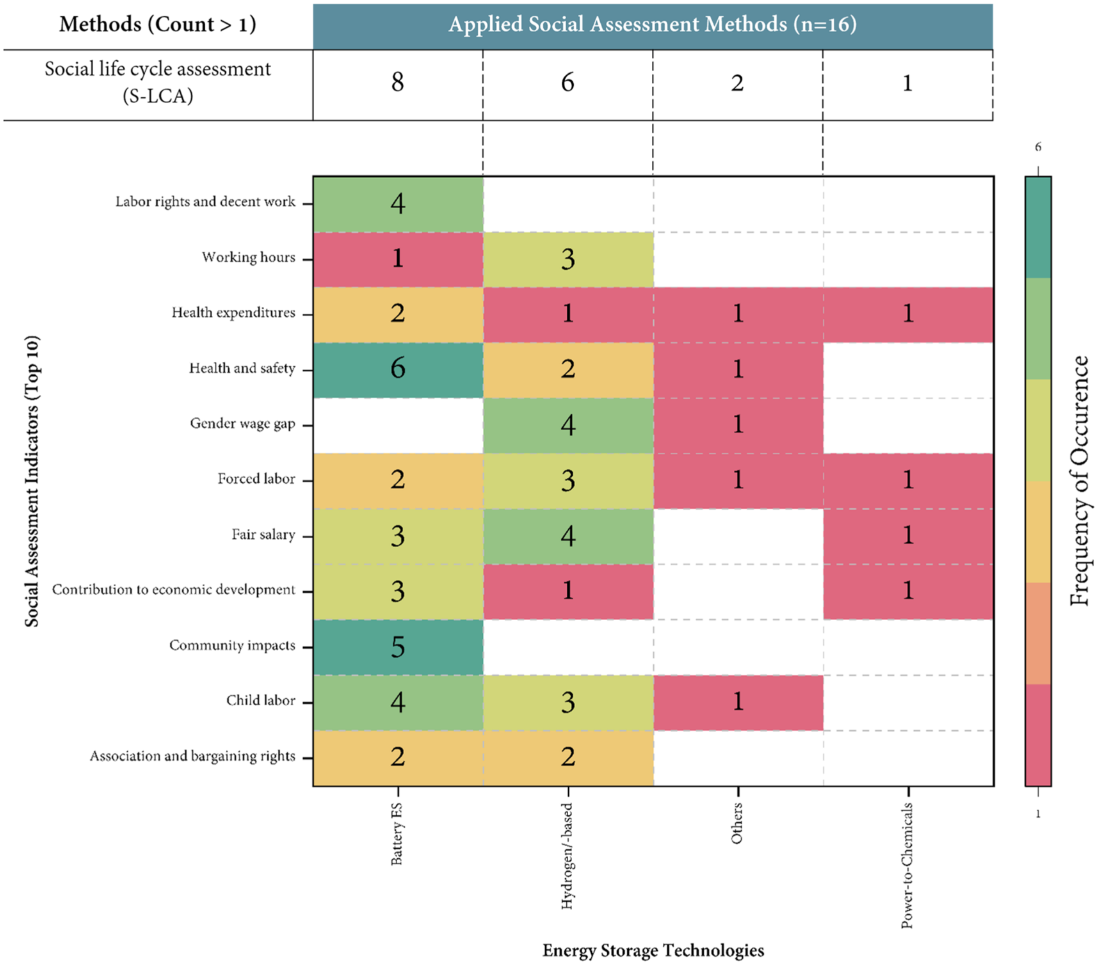


Fig. 5 Applied social assessment methods ($n = 17$) across various energy storage technologies. The heat map presents the frequency of occurrence of the top 10 most frequently used social assessment indicators for different energy storage technologies. The color gradient represents the frequency of occurrence, with green indicating higher frequency and red indicating lower frequency. Note that, an individual study may include multiple indicators, technologies and assessment methods. All studies were identified through the systematic review; those focusing on raw material supply chains or specific ES materials are grouped under 'others' or 'power-to-chemicals' for methodological guidance.

into eco-design frameworks, emphasizing supply chain considerations.[93] Furthermore, one study evaluates the social impacts of two production pathways (on-site and off-site) in EU countries.[94] Various hydrogen production technologies, such as alkaline electrolysis (AEL) and polymer electrolyte membrane electrolysis (PEM) are also assessed, focusing on supply chain and working conditions.[95–97] The social impacts of hydrogen use in services is also assessed in one study, specifically railway locomotives, considering indicators like human health, economic feasibility, safety, and scalability.[98] Another study compares the social aspects of green methanol production using green hydrogen and direct air capture with conventional methanol production.[99]

The reviewed literature primarily highlights the applicability of S-LCA for the assessment of supply chain-related social impacts. These studies predominantly focus on cradle-to-gate system boundaries, especially for resource-intensive technologies, where social risks are concentrated in raw material extraction, processing, and component manufacturing stages. This focus underscores the potential role of S-LCA in identifying social hotspots within a complex global supply chain typical of ES technologies. While some studies on batteries extend their assessment to the use and EoL phases, the collected studies on hydrogen assess production methods and utilization pathways. This is partly due to the fact that hydrogen technologies are still emerging, thus social impacts are more relevant in the production stage due to ongoing technological developments and the establishment of supply chains. The exclusion of certain life cycle stages in these studies might be influenced by the technological constraints, difficulties in data collection, and methodological complexities in capturing dynamic social conditions which limit the scope of S-LCA. Two major S-LCA databases are commonly used: the Social Hotspots Database (SHDB) and the Product Life Cycle Assessment (PSILCA) database. Both databases are used for hotspot identification based on input–output models which link economic activities to social indicators including global sector level data across various industries. These databases enable social risk assessment leveraging input–output models which slightly differ from each other. Another difference lies in the characterization factors used in each database. In SHDB, characterization factors are expressed as qualitative risk levels (*e.g.*, low, medium, high, very high) at the country–sector level, indicating the likelihood of a social issue occurring but not its magnitude. By contrast, PSILCA employs quantitative characterization factors linked to activity variables such as working hours, value added, or number of employees, allowing social impacts to be expressed in measurable units (*e.g.*, hours of child labor per functional unit). This makes SHDB particularly useful for hotspot identification, whereas PSILCA supports more detailed and comparable quantification of social impacts.

Beyond S-LCA, other methods such as Social Footprint/Social Handprint, Social Impact Assessment (SIA), Social Return on Investment (SROI), acceptability studies, and Socio-Economic Impact Assessment (SEIA) are used for social assessments. However, these methods are not captured in this review by the formulated search string, since they have a corporate-, sector-, or country-oriented perspective rather than focusing directly on ES technology in the application context. A brief introduction to these methods is provided in the SI.

Even though technology acceptance is not part of the aforementioned social assessment methods, on the social dimension, technology acceptance is a very relevant aspect, which can directly affect the realization of an ES project. The public behavioral responses, including those from pressure groups, can significantly impact the success of ES projects. This is particularly relevant for technologies with direct public visibility, such as large storage units, where concerns may arise regarding visual impacts, perceived health and safety risks, and broader sustainability implications (*e.g.*, reflected in initiatives like the battery passport).[100] Despite its importance, technology acceptance remains a field without a universally agreed definition. Many studies equate acceptance with attitudes, simultaneously considering both attitudinal and behavioral dimensions.[101] In a technological context, acceptance can be understood as an attitude towards technology, which may manifest in behaviors which either support or oppose specific proposals. Research in this field typically relies on interviews and surveys, demanding a high level of expertise in their design and evaluation. In technology acceptance studies, reliance on interview- and survey-based data presents an additional challenge: the insights are often highly context-specific, shaped by cultural, social, and regional conditions, and thus not easily transferable to other cases. This limits the availability of processable data for broader assessments of social acceptance of ES technologies. Possible solutions include the development of harmonized survey instruments, cross-country comparative studies, and integration of such primary data into open-access databases to enable more consistent and comparable evaluation of ES technology acceptance across different settings. Understanding technology acceptability is crucial for practitioners, policymakers, and decision-makers, as insights into public perceptions can guide more informed decisions and facilitate the successful adoption of ES technologies within the broader framework of sustainable development initiatives.

(i) Our analysis demonstrates that S-LCA is the most frequently used method for assessing the social impacts of ES systems. Given the critical role of social aspects in sustainability, there is a growing demand for more comprehensive assessments. The concentration of studies on batteries and hydrogen highlights a research gap: other ES technologies (*e.g.*, mechanical storage, thermal storage, or other power-to-X pathways) remain underexplored, particularly within social assessments. Broadening the scope of future assessments to these technologies would provide decision-makers with a more balanced evidence base to identify the most appropriate solutions under specific regional boundary conditions. Many of the general recommendations given in the previous sections also apply to social assessments of ES technologies, for example, the importance of a clear goal and scope definition, comprehensive system boundaries, robust data management, consideration of use phase, use of consistent functional units, and the integration of sensitivity and uncertainty analyses. Considering the available methods, the following additional recommendations need to be considered when addressing the social dimension of ES sustainability: stakeholders: integration of stakeholder participation into the assessment process to capture diverse social perspectives and increase the legitimacy and relevance of the findings.

Social impacts of ES technologies are often highly context-dependent, shaped by local communities, workers, supply chain actors, and policy frameworks. Early and active involvement of these groups (through *e.g.*, co-construction, participatory workshops, or structured interviews) helps to ensure that the assessment addresses issues of real concern and presents results in a form useful for decision-making. Such participation not only enhances transparency and acceptance of the study but also reduces the risk of overlooking vulnerable groups or region-specific concerns that may otherwise remain hidden.

(ii) *Extending the technological scope*: encourage the application of S-LCA beyond currently dominant technologies to ensure a more balanced representation of social impacts across the ES landscape.

The present concentration of studies on a few technologies leaves gaps in understanding the social implications of other ES alternatives. Broadening the scope of social assessments would provide decision-makers with a more comprehensive evidence base.

(iii) *Mixed methods*: develop and apply more comprehensive and consistent frameworks, incorporating both qualitative and quantitative indicators to improve comparability and robustness.

While qualitative approaches such as interviews and surveys capture context-specific insights and stakeholder perceptions, quantitative databases (*e.g.*, SHDB or PSILCA) provide structured, process-level information. Combining these approaches allows studies to benefit from the methodological strength of each, where qualitative methods add depth, nuance, and legitimacy, and quantitative methods ensure consistency, scalability, and comparability across technologies and regions. Leveraging the methodological capacities of complementary approaches (see SI) can thus enhance the overall reliability and decision-usefulness of social assessments of ES technologies.

(iv) *Comprehensive database*: strengthen the level of detail in modelling supply chains, especially for raw materials and component manufacturing, by improving access to and use of dedicated social impact databases.

This recommendation is directed primarily at tool and database developers, who should aim to improve the representativeness and transparency of the datasets underlying social assessment tools. However, practitioners must also be aware of the limitations of available data in the specific context of their study. While average processes and proxy data can be useful for approximating real-world conditions, their limitations in representing actual social dynamics need to be clearly acknowledged and discussed. Making these constraints explicit helps to avoid overinterpretation of results and ensures that conclusions remain credible for decision-making.

(v) *Interdimensional relations*: utilize existing economic and environmental life cycle data and models, which might be helpful in enhancing the coverage and depth of social assessments, especially in cases of data scarcity or high uncertainty.

Since many processes and supply chains are already well-characterized in environmental LCA and techno-economic analyses, these datasets can serve as valuable proxies or structural references to identify relevant actors, hotspots, and impact pathways in social LCA. Integrating such interdimensional information can help to streamline data collection, improve the completeness of system modelling, and enable more consistent comparisons across the three sustainability dimensions. Care must be taken, however, to ensure methodological coherence and avoid overextending assumptions beyond their intended scope.

(vi) *Supply chain transparency*: promote greater transparency from industry actors regarding labor conditions, sourcing practices, and governance measures, as such disclosures are essential for accurate social impact analysis.

Similar to the point on data representativeness, this recommendation is directed at data providers, who are often also among the key stakeholder groups involved. A clear understanding of supply chains is crucial because social impacts are not only sector-specific but are also strongly shaped by regional conditions. Improved traceability of supply chains allows assessment practitioners to identify the relevant stakeholder more accurately, which in turn enhances the validity and contextual relevance of the assessment results.

(vii) *Observing dynamic conditions*: be aware of the context-dependent and dynamic nature of social data in S-LCA.

Social impacts are strongly influenced by temporal and regional factors such as changes in labor regulations, governance quality, market dynamics and cultural norms. As a result, data that are accurate at one point in time or in one location may quickly become outdated or unrepresentative elsewhere. Practitioners should therefore treat social data as time- and context-sensitive, complementing them with regular updates, scenario analyses, or sensitivity testing to capture possible changes over time. Recognizing this dynamic character helps to avoid misleading conclusions and strengthens the robustness of social assessments of ES technologies.

5. Integrated sustainability assessments

Given the multidimensional character of sustainability, assessments limited to a single dimension are insufficient to support informed decision-making in the context of ES systems. While a range of ES technologies exists to meet the service demands of diverse applications, no single technology can universally satisfy all application-specific requirements. As highlighted above, the interdependencies of technical, economic, environmental and social dimensions are crucial for decisions. Improvement in one dimension can result in unintended impacts in another, also known as burden shifting.[102] Often a trade-off must be found and minimized between different criteria, which can be done with the aid of integrated sustainability assessment methods with active involvement of stakeholders. In practice, integrated assessments employ analytical methods which correspond to each sustainability dimension. However, they vary in how these methods are combined and integrated within the overall assessment framework. Side-by-side assessment results must be used for decision-making to identify the trade-offs *via* decision analysis methods. In these assessments, interpretation and communication of the results show variation and should always acknowledge the significance of decision attributes and objectives.

The conducted literature review identifies 76 studies which consider both environmental and economic assessments, whereas only one study assesses social and environmental dimensions, as illustrated in Fig. 6. Since the primary aim of the conducted literature review was to investigate the assessment methods applied in the field of ES systems, the search string did not yield a broad range of studies employing integrated assessments, and in particular, those covering all three dimensions of sustainability within the ES context. The limited

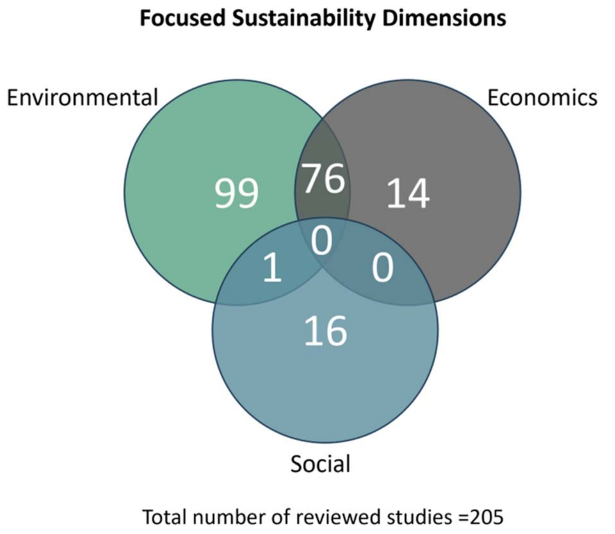


Fig. 6 Considered studies, distribution of focused sustainability dimensions.

number of integrated assessments can be attributed to the complexity and resource intensity of conducting such studies. Performing even a single type of high quality assessment (economic, environmental, or social) is already time-consuming and costly.

One important and critical observation is that assessment studies which address multiple sustainability dimensions often conduct these evaluations independently, rather than employing side-by-side assessments. As a result, methodological integration across dimensions is typically omitted, limiting the coherence and comparability of the findings. Combining all three dimensions requires interdisciplinary collaboration, large datasets, and extended study lengths, which may exceed the practical scope of conventional research projects and publication formats. Nevertheless, highlighting this gap is important, as decision-makers ultimately need more holistic insights. Stepwise or modular integration of the three dimensions, or coordinated multi-institutional efforts, may provide a more feasible path forward. For the sake of completeness and to promote integrated assessments, herein integration methods are introduced. To the authors' best knowledge, the Life Cycle Sustainability Assessment (LCSA) framework and Extended Multi-Regional Input-Output Analysis (EMRIO) are the potentially applicable approaches in ES sustainability assessments, often supported by Multi-Criteria Decision Analysis (MCDA) to facilitate decision-making across sustainability dimensions.

LCSA is a comprehensive framework that considers the environmental, economic, and social dimensions of a product, process, or service.[103] LCA, LCC, and S-LCA methods are all integrated under a unified goal and scope definition, ideally incorporating stakeholder perspectives.[104–107] Additionally, the integration of circular economy principles and material criticality into the LCSA framework has been recently recognized as crucial, considering resource efficiency concerns, growing global supply chain risks and import reliance.[108] While LCSA serves as an indicative approach for decision-making, its full potential can only be realized through comprehensive system boundary definitions and data harmonization.[109] This is particularly relevant for ES systems, where variations in supply chains and regional energy mixes can significantly impact sustainability performance. It adheres to the conventional LCA framework but includes a concluding step which presents aggregated scores for decision-making. In LCSA, the quality of assessment results and decision-making setup in terms of stakeholder consolidation play a major role. Each assessment must entail all relevant life cycle phases and stakeholder perspectives, particularly the EoL, potentially changing the overall picture regarding environmental impacts and resource use.

MCDA is a structured approach used to address decision-making problems involving multiple criteria, stakeholders, and potential alternatives by their weighting and ranking. In the ES sustainability assessment context, MCDA is helpful for comparison of specific technology alternatives, in particular through the use of Multi-attribute Decision Making (MADMindex: MADM\t: multi-attribute decision-making?>) methods (here MCDA is used as a synonym) which is often used for decision-making analysis in LCSAs. Use of multi-objective decision-making can also be relevant, but is not considered within the scope of this review. MCDA is carried out in two overlapping phases: 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 involves criteria performance measurements, weights elicitation, criteria aggregation, and results comparison. This can be done using several methods, such as compensatory (*e.g.*, analytic hierarchy process (AHP)) or outranking methods such as the preference ranking organization method for enrichment evaluation (PROMETHEE).[110,111] These methods allow for comprehensive and iterative engagement of stakeholders.[112] In any case, an MCDA must be carried out in a careful way to assure the comparability of alternatives and avoid non-practical applications without a real-world context.[113]

On a broader scope, EMRIO incorporates environmental, socio-economic, and social account indicators into the input–output matrix in contrast to MRIO which has a focus on economic flows.[114] This allows the simultaneous assessment of various sustainability indicators related to the sectoral economic activities in macro-economic terms. Common indicators include socio-economic indicators as value-added and employment generation, while environmental indicators entail global warming impacts, with the possibility to use other impact categories (*e.g.*, terrestrial/freshwater acidification, eutrophication, land use).[114–116] Social indicators considered can be both qualitative and quantitative.[117] Others have used EMRIO to analyze dependence and governance, assessing risks associated with a diversified portfolio of suppliers from countries with various governance levels.[115,116] In sum, EMRIO can be used for macro-level assessments and for investigating multiplier, spill-over and feedback effects.[118]

It is critical for all assessment and decision-making steps to incorporate relevant stakeholder perspectives in order to ensure the representativeness of the study. However, stakeholder preferences depend strongly on aspects such as spatial factors and participant type; hence, they may have limited temporal validity as they can change over time. Here, workshops integrating industry representatives, policymakers and communities can help to discuss results and obtain further input. This may result in conflicting outcomes, which complicates the provision of a comprehensive picture and clear recommendations. However, this complexity is inherent in all decisions, and consulting all stakeholder groups improves the accuracy of trade-offs for a comprehensive picture on which a robust decision is built.

6. Conclusions

Through the conducted literature review, this work shows that all necessary methodological tools are available to address ES sustainability holistically across environmental, economic, and social dimensions. However, these methods are not used to their full extent, and fail to exploit their full capacity for delivering directive inferences. This is mainly due to the way ES assessment studies are designed, often with a narrow scope aimed at clarifying doubts in a single dimension, while neglecting other aspects that may be critical for decision-making. In order to advance the discourse on the sustainability of ES systems and facilitate informed decision-making, comprehensive and multidimensional assessments are essential.

Despite the availability of appropriate methods, several constraints hinder their comprehensive application, including the absence of a universal assessment framework, disparities in methodological maturity, limitations in data availability, and the high modelling efforts required. While economic assessment methods have traditionally been considered the most established, environmental methods such as LCA and MFA have reached a comparable level of development, owing to recent advancements in measurement and estimation techniques. In the social dimension, despite the lack of methodological plenitude, notable progress has been made in recent years. Qualitative methods have increasingly been complemented by quantitative analyses, and the development of social impact databases has played a crucial role. This observation is further supported by the current, but still limited, application of S-LCA in the ES context.

Furthermore, a critical observation from the literature is that most existing assessments prioritize highly debated aspects, particularly environmental or economic aspects, rather than embracing sustainability as a whole. The prevailing objective is often to evaluate a specific technological choice in order to demonstrate environmental sustainability (mostly focusing on climate change impacts) at an acceptable cost. This approach often results in the exclusion of the social dimension and an insufficient consideration of interdependencies between dimensions, which weakens the comprehensiveness of the sustainability argument. Although it is encouraging that environmental and economic aspects are increasingly assessed together, many of these studies lack a guiding framework capable of steering the findings toward robust and integrated decisions. Surprisingly, none of the studies evaluate social and economic dimensions together, even though these two dimensions are strongly interconnected since both S-LCA and SIA methods have a strong economic orientation.

To move towards embracing sustainability as a whole in a more quantitative manner, future studies could adopt hybrid frameworks that combine environmental LCA, LCC, and S-LCA into LCSA as introduced in Section 5. Quantitative integration can be supported through MCDA, which allows weighting and aggregation of indicators across dimensions, or by employing common reference units such as 'sustainability scores' normalized per functional unit. While each of these approaches comes with methodological challenges, their application would help to explicitly consider interdependencies. Given the considerable time and collaborative effort required to conduct fully integrated studies, side-by-side assessments can serve as a pragmatic alternative for managing workload, provided that they adopt consistent goal and scope definitions, system boundaries, and functional units. This consistency enables meaningful comparison and alignment of results across the different sustainability dimensions.

It is evident that environmental impacts are frequently assessed in combination with techno-economic feasibility, reflecting a tendency toward partial integration. While feasibility studies were historically evaluated solely in techno-economic terms, and sustainability was primarily framed in environmental contexts, this shift in approach points to a recognition. While the lack of social assessments is not the sole obstacle to integrated sustainability evaluations, it does remain a critical gap. Cases such as lead-acid batteries, which are environmentally competitive for certain applications due to high recyclability but raise severe social health concerns from mining and informal recycling, or Li-ion batteries, where child labor risks in cobalt supply chains undermine otherwise favorable environmental assessments, illustrate how social aspects can overturn or fundamentally qualify conclusions derived from environmental or economic analysis alone.

As underlined by the TBL framework, consistent accounting of all dimensions is the key to sustainability. In the near future, regulatory mechanisms such as ESG are expected to contribute more substantially to establishing this balance. By providing standardized social indicators and evaluation structures, ESG frameworks can stimulate an increase in social impact analyses and support the integration of the social dimension into sustainability assessments.

In terms of technological scope of the assessments, battery and hydrogen-based systems are the most frequently assessed ES technologies. This trend corresponds with the increasing attention these technologies receive due to their critical role in the energy transition. A significant share of the studies focused on understanding the environmental and economic impacts of these systems. The recommendations need to be taken into consideration to improve the quality of these assessments.

Achieving high quality assessments is essential for their efficient use in decision-making, which requires additional efforts for the realization of stronger collaboration between regulatory bodies and academic institutions. This cooperation should potentially contribute to the promotion of more transparent, accessible, and complete data generation practices. Furthermore, it is vital to incorporate interdisciplinary perspectives into study designs in order to close existing knowledge gaps and generate assessment-based evidence to support complex decisions. To this end, structured stakeholder engagement frameworks must be employed to ensure that the perspectives of policymakers, researchers, industry actors, and society at large are adequately represented.

On the policy and regulatory side, recommendations should focus on establishing comprehensive sustainability assessment frameworks for ES systems, with clearly defined operational steps, standardized indicators, and transparent estimation methods. Finally, it is important to recognize that sustainability assessments in this field remain largely technology-centric, with limited attention given to system-level perspectives that consider deployment strategies and their broader socio-economic and environmental implications. Expanding the analytical focus beyond individual technologies to the wider system context will be essential to enhance the relevance, credibility, and utility of sustainability assessments moving forward.

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Conflicts of interest

There are no conflicts to declare.

Data availability

All data supporting the findings of this study are available within the article and its SI files. As this is a review article, no new experimental or computational data were generated. The datasets analyzed in the course of the review were obtained from publicly available peer-reviewed literature, and all sources are fully cited. Should any additional information be required, the corresponding author is available for inquiries. Supplementary information: (1) a PDF ("Supplementary Information: Assessment Method Comparison and Additional Methods for Social Assessment of Energy Storage") containing Supplementary Table 1—taxonomy of sustainability assessment methods categorized by their primary focus (economic, environmental, social) with illustrative energy sector applications—and a chapter summarizing additional social assessment methods not introduced in the main manuscript; and (2) an Excel file with six tables: SI-Table 1 (raw collection of studies for the literature review), SI-Table 2 (selected and filtered studies), SI-Table 3 (main technology groups and clustured specific energy storage technologies), SI-Table 4 (applied economic and social assessments grouped by technology), SI-Table 5 (applied environmental assessments grouped by technology), and SI-Table 6 (applied environmental and social assessments grouped by technology). See DOI: https://doi.org/10.1039/d5se00750j.

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