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Perspective

Overcoming barriers to improved decision-making for battery deployment in the clean energy transition

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SUMMARY

Decarbonization plans depend on the rapid, large-scale deployment of batteries to sufficiently decarbonize the electricity system and on-road transport. This can take many forms, shaped by technology, materials, and supply chain selection, which will have local and global environmental and social impacts. Current knowledge gaps limit the ability of decision-makers to make choices in facilitating battery deployment that minimizes or avoids unintended environmental and social consequences. These gaps include a lack of harmonized, accessible, and up-to-date data on manufacturing and supply chains and shortcomings within sustainability and social impact assessment methods, resulting in uncertainty that limits incorporation of research into policy making. These gaps can lead to unintended detrimental effects of large-scale battery deployment. To support decarbonization goals while minimizing negative environmental and social impacts, we elucidate current barriers to tracking how decision-making for large-scale battery deployment translates to environmental and social impacts and recommend steps to overcome them.

INTRODUCTION

Decarbonizing global energy systems entails two concurrent transitions: (1) The displacement of fossil-fuels in the energy supply with renewable or zero-carbon fuels and energy carriers, particularly electricity, and 2) the electrification of energy end-use applications that have historically depended on direct fossil fuel combustion. Regional plans for electricity system decarbonization for the United States (US),[1,2] and Europe[3,4] typically project the need for multifold increases in battery energy storage to maintain electricity service reliability. Scenarios for decarbonizing the US economy such as the Princeton Net Zero America study[2] project the need for a 27-fold increase over 2021 levels[5] by 2050. The European Union (EU), within its New Green Deal supported by investments of 600 billion Euros, aims at reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990) and reaching a net-zero carbon emitting economy in 2050.[6] The estimated total power capacities of the energy storage fleet to achieve these goals are 200 GW by 2030 and up to 600 GW by 2050.[7] As batteries are considered key to reaching these ambitious climate action targets, they are among the focus sectors of the European Commission's new Circular Economy Action Plan[8] and the European Union Battery Passport,[9,10] with the objective that batteries placed on the EU market should become sustainable, high-performing and safe across their entire life cycle.

Simultaneously, broader plans to decarbonize regional economies also depend on turning over the stock of on-road vehicles from gasoline and diesel powertrains to battery electric vehicles, particularly in the light- and medium-duty sectors. In the US alone, scenarios from the Princeton Net Zero America study project requirements of roughly 2,270 GWh of lithium-ion battery capacity for land transport, a 38-fold increase over the 60 GWh of capacity embedded in BEVs sold between 2010 and 2020.[11] In the EU, from 2035 on all new light duty vehicles put on the EU market must be zero emission cars, with a volume of over 11 million vehicles (annual registrations of light duty cars and vans were 11.4 million in 2021).[12] Globally, total battery capacity put on the road in light-duty EV in 2050 is projected to be between 6 and 12 TWh,[13] with a total installed battery capacity of over 50 TWh.[14]

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The development and use of a robust evaluation framework, including sustainability assessment and rigorous decision-making processes for stakeholders involved battery deployment is critical for pre-emptively minimizing negative environmental and social impacts of new energy technologies. There are numerous historical examples of perverse outcomes for technologies deployed for environmental benefit lead to high social and environmental impact. For example, the rapid deployment of biofuels under US and EU mandates in the late 2000s led to, at worst, increases in GHG emissions or at best small reductions in emissions relative to petroleum fuels, while causing deforestation and food price spikes. In the lithium-ion battery supply chain, the rapid development of cobalt supply chains first for portable electronics and power tools and later for large format energy storage applications was linked to child labor exploitation in the Democratic Republic of the Congo (DRC) prompting manufacturers to develop traceability protocols in tandem with smelter certifications to ensure supply chains did not did contain production using child.[15–17] Aluminum supply chains for automobiles–where its used in everything from engine blocks to battery foils– have been linked to forced labor and human rights abuses in Xinjiang, China, which could result in exclusion from markets with import restrictions on forced labor or that require documentation for traceability.[18] A lack of end-of-life management consideration too could result in environmental impacts. Without adequate end-of-life management for lead-acid batteries, for example, lead pollution from improperly disposed system can cause local environmental impacts. Even where a comprehensive collection and recovery program for lead-acid batteries is in place, lead pollution from recycling facilities is still present in local communities. Lead-acid batteries are currently required for most automobiles, including plug-in hybrids, and battery recycling facilities have been linked to major lead contamination in environmental justice communities in Southern California.[19–21] These impacts show the importance of pre-emptively thinking of the entire product life cycle in sustainability assessment.

While regulation tries to direct the technology deployment toward sustainability criteria, these are often falling short, partially because reliable information about potential negative impacts is lacking and technology development runs on ahead of regulation. In the EU, the recently published Battery Regulation[22] sets cutting-edge standards for battery sustainability, relying strongly on life cycle assessment (LCA), a standardized approach for quantifying potential environmental impacts of products or services along their entire life cycle.[23]However, the Battery Regulation only requires the declaration of a carbon footprint, disregarding other environmental impacts and leaving social impacts out of scope. While other legislative pieces are available on several of these aspects, such as the Critical Raw Materials Act (requiring a minimum share of EU-sourced materials to be used)[24] or the proposal for a Directive on Corporate Sustainability Due Diligence[25] (obliging companies to address negative environmental and societal impacts of their activities, including in their value chains inside and outside Europe), these are very broad in scope and fail to address battery-specific aspects. Similarly, while batteries have to declare their carbon footprint in future, EU vehicle emission standards only account for tailpipe emissions, considering EV as zero emission no matter the carbon footprint of their battery.[26,27] Their power for driving a sustainable but rapid deployment of batteries is therefore comparably limited.

A framework for decision support can assist the diverse set of decision-makers that will influence the way additional battery capacity will be deployed. These choices will translate, for better or worse, to environmental and social impacts on different populations and demographics. Here, we use the term "decision-maker" to collectively refer to the set of organizations that can make decisions which influence the environmental or social impacts of battery energy storage rollout in supporting a clean energy transition. For example, governments can make mandates or incentives which influence battery supply chain characteristics, battery manufacturers can make material procurement or design choices that affect environmental and social impacts, and customer groups can make decisions on standards for procurement that influence demand. An example of major decision-makers as referred to in this perspective is provided in Table 1.

The rapid deployment of battery capacity involves choices that include but are not limited to the selection of battery technologies and their chemistries to be deployed in each application, the sourcing of battery materials based on different technologies, the processes used in battery manufacturing, use, and end-of-life handling, and the location of industrial processes. Depending upon the context, choices in these areas are made by different decision-makers, such as regional and local governments, battery manufacturers, raw material suppliers, system integrators, recycling companies, energy producers, and energy storage owners and operators. Those choices can result in widely varying magnitudes of environmental and social impacts and their distribution between populations. Further, the extent of engagement of local communities who may be detrimentally affected by these choices will also affect the environmental and social impacts of rapid battery deployment.[28]

Here, we summarize the key challenges and recommendations for steps to overcome them on the way toward an adaptable evaluation framework for decision-makers involved in the rapid deployment of batteries. This work is the result of a 3-year project funded by the University of California Office of the President entitled "Maximizing the Environmental Utility of Battery Storage" led by the University of California – Irvine, Davis, Santa Barbara, and Los Angeles campuses, with substantial input from government, industry, community, and academic stakeholders, aimed at understanding how to facilitate a more environmentally and socially responsible deployment of battery technologies. A list of entities that participated in the workshops is provided in the Supplemental Information, Table S1. This effort consisted of four multi-stakeholder workshops focusing on different themes of data quality and availability, the state and limitations of assessment methods, decision-making, and policy. Each workshop will be described in brief in the relevant topical section of the manuscript. We present this framework by first describing the key challenges for enabling robust sustainability assessment and decision support for different decision-makers, then detailing the mechanisms for overcoming them.

Current limitations in impact assessment methods for supporting decision-making in battery deployment

We identify challenges in three key areas that currently limit the ability of decision-makers in the battery value chain – for example, raw material suppliers, battery manufacturers, recycling companies, energy storage owners and operators (such as utilities), regulators, and

Table 1. Major decision-makers influencing battery sustainability

Decision-Maker Type	Potential types of decisions made	Potential influence on battery sustainability
Federal, State, or Local Lawmakers	• Establishes mandates for supply chain characteristics for procurement by government agencies or deployment in a regional market. • Sets direct or indirect laws or goals specifying timelines for deployment of battery technologies. • Reviews applications for siting or use of battery technologies • Decides on incentives or funding for battery production and deployment.	• Sets the pace of battery supply chain development and scaling. • Requires, incentivizes, or otherwise affects specific sustainability characteristics for the battery supply chain.
Government Agencies (i.e., public utility commission; environmental, commerce or energy regulatory agencies)	• Issues regulations or standards governing deployment and performance of battery technologies. • Enforces and verifies compliance with laws and regulations. • Develops and administers incentive programs.	• Implements regulations aimed at promoting supply chain sustainability. • Sets standards that require, encourage, or otherwise affect sustainability characteristics of battery supply chains
Battery Manufacturers and Designers	• Determines specific designs for battery products. • Selects materials to be used in battery technologies based on product design. • Selects raw material suppliers to procure necessary materials needed to produce their products. • Selects manufacturing methods for producing their products	• Makes design choices that determine demand for specific materials. • Can drive demand for materials from suppliers with specific sustainability characteristics. • Makes design choices that determine environmental and social impacts from battery production.
Battery System Integrators (i.e., Utilities, Automakers, Developers)	• Sets performance and cost requirements for batteries to meet their applications. • Makes procurement decisions for battery technologies to meet mandated or voluntary goals.	• Application-specific performance and cost requirements influence demand for specific battery types and associated materials.
Materials Suppliers	• Determines where, how, and from whom raw materials for batteries are procured.	• Influences where and how mining projects are built and associated impacts.
Non-Governmental Organizations	• Advocates for policy, standards, or certifications influencing battery supply chain configurations.	• Influences the specifics of policy or standards implemented by governments and other decision-makers

policymakers – to better predict how their decisions can translate to potential environmental and social impacts. These challenges include (1) gaps in the quality and availability of data needed to characterize certain impacts, (2) limitations in the scope of life cycle-based sustainability assessment methods, and (3) limitations in decision-making approaches regarding battery deployment and life cycle management.

Gaps in the quality and availability of data

Many stakeholders will make choices affecting battery design, production and deployment, whether it is a battery manufacturer selecting among candidate electrode materials, a battery storage project developer choosing between different battery technologies, or regional government agency setting battery storage procurement standards. While the decision options available and associated trade-offs may differ, any sustainability assessment of such decisions begins with access to data. The limitations imposed by the lack of availability of high-quality data on certain characteristics of a battery's life cycle was the focus of the first project workshop held at UC Irvine in April 2019. Here, academic, government, and industrial stakeholders discussed major knowledge gaps regarding our understanding of the characteristics of a battery technology's life cycle and what the implications of those gaps were for avoiding detrimental impacts. Workshop attendees identified that a common theme was the lack of consistent, accessible, and high-quality data on the physical and social characteristics of different stages in battery technology life cycles. While challenges regarding life cycle inventory (LCI) data are not fully unique to batteries, these challenges do affect the ability of decision-makers to make decisions that more confidently improve environmental and social outcomes.

The first gap relates to timeliness and relevance based on data vintage. The data must characterize the material and energy flows across the relevant technology across its entire life, including battery production, use, and end-of-life. To this end, LCI datasets are typically generated and used as input for LCA. When the LCI of a battery is developed, the data collected reflect a snapshot in time. Battery technologies, however, can rapidly change due to technological breakthroughs in performance and cycle life, shifting material use and sourcing configurations, and design revisions to overcome new issues that are discovered. For example, lithium-ion battery cell gravimetric energy densities increased two to 3-fold between 2010 and 2020,[29–31] reducing the total amount of materials used in battery manufacturing per-unit and associated environmental impacts. Production scales, automated manufacturing and process streamlining, and shifting geographies of production can also reduce the material and energy consumption associated with battery production.[32] Therefore, LCIs of lithium-ion batteries developed more than five years ago would not reflect these advances and would not offer an up-to-date understanding of the technology's life cycle impacts or where further improvement is needed. Assessments of environmental and social impacts using an old LCI may imply issues that the state-of-the-art of the technology or practices may have already resolved, while also limiting our understanding of more contemporary issues with the technology.

The second gap is a lack of consistent data upkeep and maintenance. Once data are collected, the upkeep of LCIs for battery technologies is not performed at regular intervals. This means that the vintages of battery technology LCIs (referring to the year when the data comprising the LCI were collected) could be outdated and are likely to be inconsistent among different battery technologies. For battery technologies that are emerging or have not yet received as much academic or industrial attention, the case is even worse, since there may not even be multiple vintages of LCIs to choose from. For example, an LCA of vanadium redox flow batteries (VRFBs) published as late as 2015[33] relied upon an LCI for the technology published in 1999[34]; an up-to-date LCIs for this technology was later published in 2018[35] and 2020.[36] This causes different battery technologies to be compared at different levels of maturity as well as granularity of the LCIs leading to potentially inaccurate conclusions and recommendations. Attendees to the first project workshop identified that inconsistencies between different LCIs were a regular barrier to having confidence in the results of comparative LCAs.

The third gap relates to data accessibility. LCIs that reflect the state-of-the-art of a battery technology and its supply chain are often closely guarded since proprietary information and trade secrets are strategies used by a given manufacturer to maintain a competitive edge over other manufacturers. Releasing the detail of such data (e.g., energy demand, bills of materials, manufacturing yields) may compromise such an advantage, rendering many battery manufacturers to be hesitant in sharing such data to any kind of centralized, accessible repository without anonymization and/or certain details redacted. Often, manufacturers may only agree to release such data if it can be anonymized, or once the advancement it reflects has become outdated, or is no longer protected by patents, rendering the data that researchers and practitioners conducting assessments can access to be continually behind what would be considered the state-of-the-art or representative. Attendees to the first project workshop identified that inability to access up to date LCI data could cause corresponding LCAs to identify problems that may have already been addressed in newer iterations of a product.

The fourth gap is data coverage, which can influence the system boundaries of the resulting LCA. Data representing the resource flows associated with a technology are often unavailable or widely variable for specific life cycle stages.[37] This is the case for battery technologies in pilot production, that have not deployed enough representative systems, or when a prospective assessment is undertaken.[38,39] Some life cycle stages may have missing information. Battery LCAs often lack information about disposal or recycling, so exclude this life cycle stage or treat them inconsistently across studies.[40] For example, emerging battery technologies such as redox flow batteries do not have a standardized process for recycling or disposal at the end of their lifetime, as each manufacturer has different arrangements and these systems have not been deployed long enough for these arrangements to be implemented. Therefore, it may not be feasible to include the end-of-life stage in assessments focused on flow batteries or in comparisons between flow batteries with other battery technologies until data on the processes used to dispose or recycle these systems become available.

Finally, the fifth gap is related to the dearth of information on social impacts. Specific data regarding the social impacts associated with battery production, use, and end-of-life are not currently available. Social life cycle analysis (S-LCA) frameworks have emerged over the past two decades as a complement to conventional LCA, with indicators focused on impact categories such as human rights, working conditions, socio-economic repercussions, cultural heritage, and governance. In that time significant progress has been made in developing inventory indicators as well as methods and guidelines for the identifying and collecting data regarding those indicators.[41,42] Some S-LCA specific databases such as the Social Hotspots Database and the Product Social Impact Life Cycle Assessment database are available, and other generic statistical databases concerning economic development, labor conditions, wages, education and other areas provide relevant other raw data. However, no inventory of social impacts for battery systems has yet been developed. This renders it difficult for policymakers to make policies that substantively address issues in battery technologies.

Limitations of life cycle assessment-based methods for sustainability assessment

The assessment stage organizes and integrates the data drawn from the inventory, quantifying the impacts of the technology across its life span in each impact category. Comparison of sustainability assessment outcomes for different battery technologies enables decision-makers to identify trade-offs presented by the alternatives. This article focuses on the use of LCA methods for this assessment. Evaluating the readiness of LCA-based methods for sustainability assessment of battery technologies was the focus of the second project workshop held at UC Davis in October 2019. Here, researchers from academic and national laboratories, as well as state government, utilities, and environmental non-governmental organizations discussed the suitability of commonly applied practices in LCAs for addressing key knowledge gaps regarding the battery life cycle and the relevance of common impact metrics to characterizing environmental and social impacts over different jurisdictions.

LCA and its variants are widely used to assess the resource and energy consumption, emissions, and associated environmental impacts of battery products across their life cycle stages. Some LCA studies compare the environmental impacts of different battery technologies in the context of particular applications such as grid energy storage,[43,44] while others compare electrified technologies (i.e., electric vehicles) against incumbent and competing technologies, with one example even including social impacts.[45] Although a robust literature of LCA focused on battery technologies exists, particularly for technologies that have been or are projected to be widely deployed (i.e., lithium-ion, lead-acid,

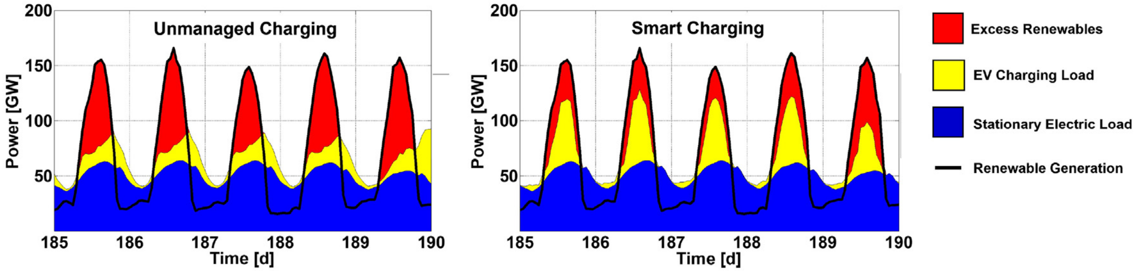

Figure 1. Alignment of electric vehicle charging loads with renewable generation under unmanaged and smart charging scenarios on a prospective year 2050 California grid

Sourced from Forrest et al.[47]

nickel-metal-hydride), gaps still exist in the scope and resolution of LCA methods that have limited its ability to more comprehensively inform how a decision-maker's choices map to environmental and social impacts. Here, we identify the following gaps:

The first gap is that LCAs of battery technologies are often attributional, meaning that they assess the environmental and social impacts of a battery product based on their interaction with a static system and further assume that the production of the product does not change that system. Attributional LCAs (a-LCAs) are important for understanding the performance of the status quo for the product and identifying dominant contributors and impacts associated with the product. Attributional LCAs, however, inherently limit understanding of how making different choices can improve or exacerbate negative impacts on a system level. For assessments to be more useful for decision support for different decision-makers, consequential LCAs (c-LCAs) which are inherently set up to address how changes propagate to impacts, need to be conducted. However, unlike a-LCA, c-LCA requires a far more complex modeling approach, including the use or creation of future scenarios regarding technology development, energy demand and other socio-techno-economic parameters, which in turn require integration of economic models, energy system models and socio-demographic predictions with LCA. Consequential LCAs for battery technologies do exist in the literature[40,46] but are relatively rare compared to attributional LCAs, are typically limited to a specific aspect, and often do not capture certain critical interactions between battery technologies and the broader energy system.

The second gap is that LCAs of battery technologies often have limited resolution of how such systems operate temporally and interact with the electric grid. Such studies often use scenarios for different electricity mixes as inputs to battery charging, but this approach does not resolve how battery systems – whether for stationary energy storage or transportation – interact with the electric grid. The mix of electricity used to charge a battery system depends on time-varying conditions on the electric grid, particularly when interacting with grids that incorporate large capacities of variable renewable energy resources such as wind and solar. Charging a battery at a given hour (i.e., when solar generation is abundant or in excess) will incur a different impact than charging the same battery during a different hour (i.e., when renewable generation is low and fossil fuels are used to meet incremental additional electric load), as shown in Figure 1.

When batteries are used for grid energy storage, another limitation is a lack of resolution regarding how electricity discharged from the system offsets or avoids the use of other electricity resources on the grid. For example, a battery used for grid energy storage may charge during the daytime with excess solar generation and discharge the stored electricity during the early evening and nighttime hours, when solar generation is limited or non-existent. The discharge of electricity during those hours avoids the use of fossil fuel-based generation that otherwise would need to be used to satisfy the electric load, reducing environmental impacts. There is also a need to better capture via adequate functional units the diversity of services that grid-connected battery systems can provide for the electric grid and their corresponding environmental benefits (e.g., for capacity-based services such as contingency reserves or frequency regulation versus energy-based services such as renewable generation time shifting). Better resolution of the different services that battery systems provide for the grid are also associated with different duty cycles which will affect battery lifetime, a key factor in life cycle environmental impacts for these systems. Certain chemistries may be more amenable to withstanding certain duty cycles than others with minimal degradation in their usable lifetime. Additionally, when batteries are considered unable to perform a given function, these systems may still be reused to perform a second, less demanding function, extending their environmental benefits. However, understanding the extent of these potential benefits requires a more highly resolved understanding of how battery systems interact with the electric grid.

The integration of electric grid dynamics and LCA of energy storage is starting to occur in the research literature, notably in studies for the French electricity system[48] and for the US Western Interconnect.[49] However, this practice is somewhat nascent with many methodological uncertainties remaining and is not yet being implemented into decision-making for battery deployment or energy systems planning.

The third gap is that there are also limited and inconsistent results accounting of battery end-of-life on environmental results.[37,40] Presently, much of the currently deployed battery capacity has not yet reached the end of its useful lifetime. Key exceptions are lead-acid batteries for on-road vehicles or backup power and small lithium-ion batteries for consumer electronics, which have a much longer history of deployment. Of these, lead-acid batteries used for automotive starters or uninterruptable power supply (UPS) have a large-scale, commercially operating infrastructure to support their end-of-life with high rates of collection and recycling. Similar infrastructure for recycling lithium-ion batteries exists at a smaller scale.[50] Collection and recycling rates for lithium-ion batteries are not well known[51] but ambitious targets have been set in jurisdictions such as the EU.[52]

Because of the uncertainty in how end-of-life batteries will be managed, and even the recycling technologies that will be available in the coming years and decades, composing LCIs that contain the contributions of battery end-of-life has a high degree of uncertainty and/or can omit important processes or steps in the disposal or recycling process, even though LCAs containing battery disposal and recycling have been conducted.[53]

The fourth gap is that the metrics for measuring environmental impacts often lack specificity that enable them to be actionable by decision-makers. LCA methods include a set of accepted environmental impact indicators[54] that translate the emissions of substances to different physical domains (land, air, and water) to different types of environmental impact types. There can be difficulty, however, in translating generalized environmental impact indicators to impacts on specific regional ecosystems and populations. Certain environmental impact indicators such as global warming potential (GWP) are straightforward to interpret since they characterize impacts that occur on a global scale. Other environmental indicators, however, often lack the spatial specificity to translate to regional impacts and are not so easy to interpret. For example, the environmental and health impacts of air pollutant emissions are highly localized, as are impacts from water use or water pollution. The lack of localized specificity regarding the contributions of processes in different life cycle stages to environmental impact indicators can limit the extent to which the results of LCAs for battery technologies can be used for decision support. Developing a set of relevant metrics that apply to all jurisdictions and all scopes of sustainability assessments for battery technologies may not be possible. There may be a need to re-evaluate existing environmental impact methods and determine the additional region-specific detail to transform these metrics into ones that are more usable for decision support by using region-dependent characterization models and factors to evaluate impacts that are not global in scope.

The fifth gap is that there are numerous aspects that cannot be covered by 'classic' LCA, because many impacts are not direct and static environmental impacts. One concern with large-scale battery deployment is resource availability and material criticality. While impact assessment methods typically include resource depletion as impact category, resource demand impacts have several dimensions. One of them is criticality i.e., geopolitical aspects related to supply risk and corresponding potential for disruptive impacts on the economy. Methods for quantifying supply risk are available,[55] but not considered in LCA (due to the environmental focus). However, as the recent Russian invasion and the subsequent disruption of supply chains have shown, the corresponding societal impacts can be very relevant. The second aspect, resource constraints, is related to consequential assessments, and is needed to foresee resource limitations and adopt steering policies. Again, several works are available that raise substantial concerns about the viability of a global large-scale deployment of batteries due to insufficient availability of key resources such as cobalt, nickel or lithium.[56,57] However, material criticality limitations for decarbonizing the world economy and required policy guidance in terms of material efficiency for energy storage (i.e., how much battery capacity can we afford?) remains widely unanswered.

The sixth gap is that conventional LCAs of battery production, use, and end-of-life do not typically consider social impacts of those activities. As noted above, S-LCA is increasingly used to assess the social impacts of diverse activities, including human rights, working conditions, cultural heritage, governance, and socio-economic repercussions. Consideration of social impacts is critical in decision-making regarding large-scale energy storage systems deployment. For example, the regional distribution of different types of resource extraction and environmental impacts has significant equity and justice implications not traditionally reflected in LCA impact assessment methods, especially since the effects of these processes and impacts are often disproportionately concentrated in historically exploited and economically disadvantaged communities – in both domestic and international contexts.[16] The use of environmental impact indicators in the absence of social impact indicators may reinforce existing inequities in the distribution of impacts and benefits between regions and population segments. Here, significant gaps remain in existing methods for S-LCA and in particular the development and standardization of social impact indicators and metrics, as well as the unavailability of associated data as discussed above.

Barriers to decision support and policy development

It is not enough, however, to simply identify trade-offs among potential battery technology alternatives. Decision-makers must evaluate those trade-offs and determine which alternatives present the most acceptable mix of positive and negative impacts. Enabling decision-makers such as battery manufacturers, battery vendors, and purchasers in government or private sectors to track how their choices may directly or indirectly translate to environmental and social impacts requires that information from relevant sustainability assessments is accessible, transparent, and incorporated into the decision-making process. It also requires that those decision-making processes effectively address the trade-offs presented by the alternatives under review.[58]

Decisions regarding the deployment of battery technologies are made by a variety of parties in a range of circumstances. For example, battery manufacturers decide what materials to procure from what supplier to produce a battery system. Battery system vendors decide which technologies and system designs to construct and market for that application. Purchasers of battery energy storage systems such as public utilities, investor-owned utilities, and community choice aggregators decide what system to procure and use it for their needs. Lawmakers at the state and local levels and regulators such as the US Environmental Protection Agency or the European Commission create mandates and incentives intended to drive the development and adoption of battery energy storage, decisions that directly affect decision-making by the other parties. Regional community advocacy groups make decisions to advocate for or against mandates and incentives, potentially affecting the upstream supply chain. Identifying barriers that limit the translation or implementation of information regarding potential trade-offs or co-benefits produced by methods such as LCA was a primary focus of the third and fourth project workshops, hosted virtually in 2021 by UC Irvine and UC Los Angeles. The third and fourth workshop brought together academic researchers with governmental and non-governmental entities to discuss the differences between the types of information produced by tools such as LCA in the research space and the types of information that are most valuable to different decision-makers. These workshops identified whether different stakeholders incorporate information from sustainability assessment and if so, how this information was or was not influential in decisions for energy storage procurement or design decisions. Workshop discussions identified two critical challenges that must be addressed: How do we integrate the information from sustainability assessments into stakeholder decision processes? And how do we ensure the quality of decision processes? Here we identify primary limitations in accomplishing these objectives based on the workshop discussions.

The first barrier is that meaningful, accessible data and information produced by sustainability assessments may not be available and understandable to decision-makers. It is foreseeable that LCI generation and sustainability assessment will be performed by a variety of different parties, depending upon the context. These parties will require access to data and information in two scenarios. The first is access to LCI data for the entity performing a sustainability assessment—be it a private project developer creating a proposal or a utility preparing an energy storage development plan. The second is access to sustainability assessment results and supporting materials in making a deployment decision.

The second barrier is that different decision-makers may not have a systematic method of assessing tradeoffs between decision alternatives. For a given energy storage application, a sustainability assessment will provide input for a decision, usually the selection of one storage solution from a set of alternatives. The alternatives under consideration will likely present differing trade-offs among the relevant impacts.[59] For example, one alternative may perform well with respect to ozone depletion but poorly regarding human health effects, while another may perform better with respect to both indicators, but worse with respect to a social impact indicator. While the sustainability assessment can measure the relative performance of the alternatives across indicators and thus identify trade-offs, it does not provide the means for balancing those trade-offs. Decision-makers will need decision support methods and tools to assist them in identifying the relative importance of each impact indicator (also known as weighting) and systematically sorting through the tradeoffs to elect a preferred alternative.

The third barrier is that sustainability assessment methods will only be effective if they are incorporated into decision-making processes for the evaluation and selection of battery energy storage technologies. However, policies to drive adoption of rigorous decision-making are not currently in place. New policies are needed to ensure that decision-makers engage in careful assessment of the impacts of potential technologies and deliberate, rigorous evaluation of the trade-offs presented. A good example is the new Battery Directive currently being developed by the European Commission. It requires batteries being placed on the market in future to be accompanied by a carbon footprint declaration. This carbon footprint is essentially based on LCA and backed up by a detailed guidance on how the carbon footprint shall be determined. While still with significant improvement potential, it is a step toward the integration of LCA into policymaking, and a better coordination between the needs that policymakers have and the information that LCA practitioners can provide (in terms of data, assessment methods and models) would help to increase policy impact.

The configuration of such policies depends upon a variety of factors, including the legal authority of the policymaker, the decision context, the capacity of the decision-maker, the impacts on different stakeholders, and the nature of the barriers to adoption of the method or tool. It is further complicated by the complex nature of the socio-technical system for electricity generation, transmission, and storage in different regions. Decisions affecting technology choice occur at multiple public (state, regional, local) and private (battery vendor, project developer, investor-owned utility, public-owned utility, CCA, etc.) levels in the shadow of diverse public and private regulation. Thus, the policies must be developed with all these factors in mind.

Developing an evaluation framework for large-scale battery deployment

To enable decision-makers involved in facilitating rapid battery deployment to meaningfully incorporate environmental and social impacts in their decision-making, we propose steps to overcome the barriers described in the previous section to enable the development a robust evaluation framework with three components: (1) Data generation, curation and dissemination; (2) sustainability assessment; and (3) trade-off analysis and decision-making. Here, we describe the features and function of each component and the steps needed to develop such a framework. Visually, the framework is presented in Figure 2.

The general characteristics of this framework are summarized as follows:

Modular

No single decision-maker will likely participate in every component; therefore, this framework must be capable of synthesizing contributions – whether data, methods, or other tools – from different decision-makers. For example, consider the case of a developer responding to a request for proposals for battery storage by a utility. Data regarding the performance of a particular battery technology or product may be generated by the manufacturer using methods and metrics established by a government agency or non-governmental organization. That data, along with other data relevant to social or environmental impacts generated or curated by other parties, may be used by the developer to perform a sustainability assessment of its proposed project, as would competing developers. In turn, the utility would evaluate the respective proposals and sustainability analyses, using decision support tools to evaluate the trade-offs presented by the competing proposals.

Flexible

The proposed framework is intended to be sufficiently flexible and broad to account for various battery technologies across chemistries, technology readiness levels, form factors, and applications. A framework that is technologically agnostic is important for ensuring that different battery chemistries and form factors can be assessed in specific applications or even compared across applications.

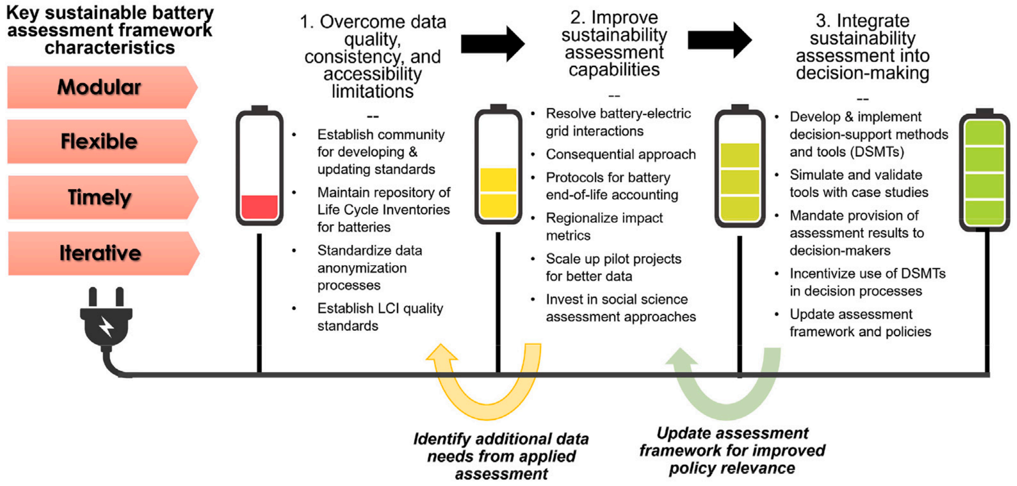

Figure 2. Visual representation of the proposed evaluation framework for rapid battery deployment

Timely

Battery technologies are rapidly evolving, not only in terms of their operational performance, efficiency, and materials composition, but also in terms of the configurations of their supply chains, manufacturing, and disposal processes. Due to the time required and institutional barriers for gathering data to comprise life cycle inventories for these changes, LCAs of battery technologies typically do not reflect the effects of these changes. The framework is intended to capture the effects of changing supply chain configurations or technology improvements more quickly, or alternatively to assess different future scenarios to support stakeholder decision-making.

Iterative

While the framework is presented as a set of sequential steps, each of the earlier stages is intended to be continually updated based on needs identified from the experience in implementation in the later stages (data, assessment, policy design). To stay relevant as the large-scale deployment evolves, data, assessment methods, and policy must be refined to incorporate lessons learned from practical experience.

Overcoming data limitations

To overcome the gaps in data availability and quality, the following steps should be taken.

Establish a community of experts to develop and implement standards for re-evaluating and composing LCIs for existing and emerging energy storage technologies at regular (i.e., 5-year) intervals

Developing LCIs for existing and emerging energy storage technologies requires both resources and a diverse array of expertise involving academic, industry, and government entities. The capability to reevaluate and recompose LCIs of existing and emerging energy storage technologies at regular intervals, a community of experts needs to be established to (1) develop agreed-upon methods and evaluation intervals and (2) carry out the work of gathering updated data and recomposing the LCIs.

This community should be convened by entities that (1) have the expertise to independently assess the quality of energy storage LCIs produced by industry and academic researchers, (2) have access to relatively stable funding sources that are not as dependent on securing individual grants, and (3) are positioned to host and document data for public access. A robust example for the United States is a US Department of Energy National Laboratory. For example, the National Renewable Energy Laboratory (NREL) has established precedent via their Life Cycle Assessment Harmonization project[60] focused on harmonizing and continually updating data on the life cycle greenhouse gas emissions of electricity generation technologies. A similar initiative for energy storage technologies will be beneficial.

Develop and maintain a centralized repository of LCIs for current and emerging energy storage technologies by vintage

In composing LCIs, researchers and practitioners will often look through available literature and use whichever datasets they can find. Having a centralized repository of LCIs conducted at regular intervals can enable clearer access to data of different vintages. This practice is also proposed for battery performance data in the Battery Data Genome.[61] Precedent for hosting such data exists in the US: NREL hosts datasets for the life cycle greenhouse gas emissions of electricity generation technologies that are continually updated as new research is produced.[60] A similar, albeit expanded structure for LCIs of energy storage technologies will be beneficial and can be international in scope. This requires developing a data quality and management process for the repository, setting up and maintaining a server and ensuring compatibility with existing LCI databases such as EcoInvent.[62,63] The community of experts should be in charge of coordinating and managing the installation of such a repository.

Establish minimum- and preferred-quality standards for LCIs of battery technologies for use in LCAs of specific applications

To ensure consistent interpretation of LCAs of battery technologies when used in specific applications, whether individually or in comparison to each other, it is critical to establish agreed-upon minimum- and preferred standards for the system boundaries, methods, and level of detail required for an LCI. These standards can be adjusted for different applications of battery technologies, such as those in stationary storage versus mobile applications. Development of these standards should be facilitated by the community of experts convened to maintain and regularly update LCIs as described previously. Here, researchers with expertise in LCA methods and metrics for quantifying environmental impacts should establish, for a given battery application, 1) the system boundary for data collection required to ensure accounting of major impacts from the battery's supply chain, 2) the resolution (granularity) of detail for data on subsystems included in that system boundary, and 3) what methods are used to compile such data. These standards will differ for different applications and while fundamentally proposed from a research standpoint, will be continually refined by input from non-governmental organizations and industry stakeholders to ensure that these standards facilitate LCAs or other assessments that adequately capture the types of impacts of interest.

The publishing of these standards can also be formalized by inclusion as ISO standards and compliance displayed by an ISO certification. From an adoption standpoint, government entities such as legislatures or regulatory agencies can choose the level of LCI standards compliance that must be met for resulting LCAs to be formally considered in policymaking or funding decisions. Such a practice is already in place for building material purchases in California.[64] It is not necessary that stakeholders such as battery manufacturers provide all of their data, but rather that participating stakeholders agree to comply with an agreed-upon set of standards. An example for how this can be accomplished exists for the solar industry through the International Energy Agency Photovoltaic Power Systems Programme.[65]

In Europe, the European Commission (EC) has been working on the development of the product environmental footprint (PEF) method with the aim of creating a uniform standard for conducting LCA studies, agreed with industry. This method is currently being cast into legislation by the new Battery Directive, making a carbon footprint declaration according to the PEF standards mandatory. The state of California in the US now requires environmental product declarations (EPDs), which must be compliant with ISO 14025, for procurement of five key building materials, with limits on maximum carbon intensity for procured materials.[64,66] The development of quality standards should be based on such existing methods, ensuring alignment with current legislation and reducing the need for new standards development.

With minimum-quality standards established, LCIs of different battery technologies can be evaluated for acceptable completeness for use in LCAs of a given scope. Data gaps or quality gaps can be identified, and a structure that incentivizes manufacturers of the technology or other relevant entities to conduct their own assessments should be established to fill in the data gaps. Develop incentives and, where appropriate, requirements for manufacturers to provide data meeting minimum quality standards.

Develop a process for manufacturers to provide data without compromising their competitive advantage

Developing such a process can include the implementation of methods for data anonymization and aggregation before publishing, while still maintaining sufficient detail to be useful for conducting LCAs. Even LCA results are helpful in this regard, allowing validation of the available detailed models in terms of representativeness. To develop a process that gains significant participation, the development process will require ongoing dialogue between battery manufacturers, policymakers, and LCA practitioners, further highlighting the need for establishing a community of experts to develop and maintain LCIs for battery technologies.

This community will facilitate dialogue between stakeholders to establish (1) the format, type, and level of detail for LCI data or LCA results provided by battery manufacturers that strike an acceptable balance between intellectual property protection and reflection of the state-of-the-art configuration of a battery technology's life cycle and (2) an agreed-upon stakeholder review procedure for release and use of datasets developed by battery manufacturers. The latter should establish criteria to be met from two independent perspectives: (1) criteria set by researchers for acceptable level of detail for manufacturer-provided data to be useful (i.e., standards for the LCIs or LCA results) and (2) criteria set by industry stakeholders for limiting the ability to reverse engineer trade secrets from such data. An ongoing effort to address this for greenhouse gas emissions relating to batteries is presented in the Greenhouse Gas Rulebook by the Global Battery Alliance.[67]

Improving LCA-based sustainability assessment methods

To improve the capabilities of sustainability assessment methods to better enable tracking of how stakeholder choices translate to potential environmental and social impacts, the following steps should be taken.

Improve the integration of electricity system modeling into life cycle assessment methods for battery systems

Separate from LCA, capabilities exist for modeling the operation of the electric grid that capture how battery systems participate in the dispatch of electric grid resources and resolve the dynamics of how battery systems are operated with respect to charging and discharging over time. Regular integration of these capabilities, along with the development of agreed-upon standards for how this integration is accomplished, more accurate characterization of the use phase of battery systems to the level needed for more confident decision-making. While this practice is starting in the research literature,[48,49] more development and widespread practice is needed to mature these methods for use by decision-makers. Open data on electricity generation, but also energy system models are increasingly available for many countries. Linking these with LCA tools would enable a more meaningful modeling of the use-phase and the corresponding environmental benefits of storage.

Improve resolution of the different types of services that battery systems can provide and their subsequent environmental benefits via consequential approaches

The use phase of battery systems is where the benefits of using these systems manifest. These systems can provide many different functions to support the integration of renewable resources and the operation of the electric grid. To better understand the benefits of deploying battery systems, the capability to capture the full range of services that battery systems can provide to the grid must be developed. The provision of each of these services has the potential to provide environmental benefits by preventing the use of other, higher-polluting resources that already exist on the grid or preventing the construction of newer higher-polluting resources in the first place, avoiding their associated environmental impacts.

Develop best practices and protocols for end-of-life options for the current and emerging technologies used for energy system applications

Since most of the currently deployed battery capacity has not yet reached its end-of-life, characterization of the end-of-life options and their impacts for different battery technologies is less mature compared to that for battery manufacturing and use. While certain battery technologies have significant field experience for their end-of-life processes (i.e., lead-acid) and others are starting to gain such experience (i.e., lithium-ion), an understanding of the potential advantages and disadvantages of different end-of-life options for other battery technologies are lacking. Specifically, the lack of available data for comprising LCIs of current state-of-the-art and emerging battery chemistries needed to resolve the effects of recycling these systems and making decisions based on their inclusion in LCAs is caused by a lack of recycling operations occurring at scale. Scoping and evaluation of the practices and protocols for the end-of-life options for other battery technologies, particularly emerging technologies, and implementation of these protocols early in the deployment of end-of-life processes will better enable them to be compared on a consistent basis with incumbent technologies.

Re-evaluate and improve environmental impact assessment methods to make them more regionally relevant for decision support

To ensure that the results of LCAs for battery technologies can be useful for decision-makers – product designers, policymakers, or community advocacy groups, existing environmental and social impact indicators must be translated to tangible, regionally-specific effects along spatial and demographic lines. The context of which environmental and social impacts are most important for regional populations should inform which impact indicators should be assessed, and spatial or demographic bounds or foci for those indicators should be used. For example, regulators for a region such as Southern California may focus on water depletion and air pollutant metrics when evaluating processes situated in that region, since this region is subject to frequent drought and typically experiences degraded air quality.

Implement expertise from social life cycle assessment and other social impact assessment tools (including equity metric screening methods) in developing and applying metrics that characterize social impacts and benefits of battery technology deployment into evaluation frameworks

Environmental impact indicators by themselves do not capture important social impacts, including health and safety, human rights, working conditions, socio-economic repercussions, cultural heritage and governance.[42,68,69] Consideration of such social impact categories, including the distribution of the impacts among domestic and international regions and population segments, is critical to sustainability assessment. A variety of methods and tools have been developed to facilitate systematic assessment of social impacts, including social life cycle assessment (S-LCA) and sustainability assessment using multi-criteria decision analysis. Since these approaches are relatively new and have not been extensively applied in the energy storage context, further development and standardization is needed to support widespread use, particularly in regulatory settings. Case studies can be utilized to augment or in place of S-LCA.

In addition, these approaches can be complemented with related tools. For example, screening tools,[70,71] which have been used by several state-level agencies and federal agencies in the United States, combine several economic and social demographics to map where vulnerable communities exist geographically and overlay what pollution and other burdens are placed upon those communities. This type of tool provides a visual understanding of where vulnerable communities are located geographically and what pollution burdens are placed directly on or near these communities. Particularly for siting decisions related to battery technology, a similar mapping tool would provide a clearer sense of where benefits and burdens are distributed. Similarly, mapping whether battery technology is deployed and overlaying socio-economic demographics could provide an understanding of what communities have access to battery technologies and which do not.

Integrate sustainability assessment into decision-making

Here, steps needed to build capacity to evaluate the results of sustainability assessments are described. In particular, the sustainability assessment will likely identify trade-offs among the battery technology options. For example, while one option may raise concerns regarding negative environmental impacts of one sort, a competing option might instead present potential adverse social impacts. Methods and tools for resolving such trade-offs must be developed and then ultimately adopted by relevant decision-makers. The first set of steps aim to establish methods and tools needed for rigorous such decision-making.

Developing relevant and appropriate decision-support methods and tools (DSMT) and guidance to assist in responsible decision-making

Decision-making is highly contextual, and the decision support tool must fit the context. There are a variety of decision support methods that could be applied in this context. Decision methods can be narrative, structured, and analytical.[72] Narrative methods call for holistic, qualitative balancing of the data and associated trade-offs to reach a decision. Structured approaches provide specific, systematic guidance to the decision-maker, such as a decision tree or a set of specific decision rules or heuristics. Analytical methods such as multicriteria decision analysis (MCDA) include mathematically based formal decision analysis tools to assess data and generate rankings in different ways. Selection of the particular method will depend on the specific decision context, including the institutional capacity of the decision-maker. For example, a decision support tool crafted for local land use commissions generating individual overall scores for candidate technologies could mask important value-based tradeoffs.

Researchers have developed a variety of analytical methods relevant to the selection of energy storage and generation technologies.[69,73] Some of these approaches use LCA as input[74] while others integrate LCA and MCDA into a single method.[75] The development of decision support methods appropriate for the context of grid-level energy storage must consider multiple factors, particularly where a wide range of stakeholders are involved in the decision-making process. These factors include (1) the need to craft methods that can be used and understood and consequently be accepted by non-experts in decision analysis, (2) managing diverse types of quantitative and qualitative data, (3) identifying approaches for weighting of the relevant impact indicators (typically called decision criteria or attributes in MCDA) and, (4) understanding and communicating the effects of uncertainty regarding attribute weights and performance data.[59,69] The process for developing such DSMTs must include meaningful engagement with expected users and stakeholders regarding these and other relevant factors. To that end, it would begin by scoping the specific needs, capacities, and values of the respective users and stakeholders.

Implement case studies to validate and improve DSMTs and demonstrate their use on the ground

Case studies can provide valuable information and experience needed to ensure that a DSMT is useful, robust, and tractable for the intended users. Moreover, case studies can build confidence in and support for the use of DSMTs among users and stakeholders.

The second set of steps ensures that the DSMTs are implemented by the relevant decisionmakers.

Establish mechanisms that enable and encourage battery vendors to make available relevant data and information on their technology to decision-makers

Digitalization of product data and information offers an effective means of dissemination, enhancing transparency, and streamlining the data collection and curation process.[76] Digital product passports (DPP) have been proposed in a variety of contexts. A DPP is ''a dataset that summarizes the components, materials, and chemical substances in a product, and information on reparability, spare parts, and proper disposal instructions.''[77] The European Union's battery regulation includes a digital passport requirement for industrial batteries and electric vehicle traction batteries that contains information about battery parameters such as nominal energy or lifetime, but also recycled content and the carbon footprint of the battery.[10] The scope of data for such passports would be extended to include the full range of LCI data, including data relevant to sustainability concerns. The establishment of such mechanisms in different markets can help downstream decision-makers make more informed decisions to improve performance on sustainability metrics.

In some cases, the party deciding among potential battery energy storage technologies/proposals will depend upon the project developer to perform the sustainability assessment. Since the assessment will focus upon the particular project context—including local and regional conditions and attributes—the results of the assessment and supporting materials would not be included in a DPP. To ensure a rigorous and transparent decision process, a mechanism to ensure that the decision-maker and stakeholders have access to the assessment methods, results, and supporting information as needed.

Develop and evaluate a set of context-specific proposed policies mandating or incentivizing use of DSMTs for energy storage decision-making

Relevant policymakers at the state and regional levels, as well as private decision-makers such as investor-owned utilities and community aggregators, should develop explicit policies incorporating rigorous evaluation frameworks, including DSMTs, into decision-making processes. While policy development calls for expert input it also requires participation from a broad range of stakeholders to reach an effective and equitable outcome. Broad participation enhances the breadth and depth of information regarding the socio-economic system in question and the scope of alternative policies considered. It also ensures that the values and preferences of all affected parties are taken into account. The California Carbon Capture & Storage Review Panel formed by the CPUC, the CEC, and CARB in 2010 is an example of such an initiative. The panel, consisting of members from industry, trade groups, academia, and environmental organizations, was charged with identifying and evaluating policies and legal frameworks relating to CCS's potential role in meeting the state's needs [35].

Generate simulated case studies to assess the benefits and limitations of proposed policies

Electric grids are more than just infrastructure; they are part of complex socio-technical systems.[78] That complexity makes the selection of policies aimed at changing system behaviors such as decision-making regarding energy storage particularly difficult. Small changes to a complex system can lead to surprising consequential shifts in outcomes. In developing such policies, policymakers should take advantage of tools available to simulate the implementation and impacts of potential policies. Such tools include desktop simulations, scenario analysis, agent-based modeling, and socio-technical network analysis (STNA).[78–80] For example, STNA has been used to evaluate policies intended to enhance electric grid resilience.[78] Agent-based models have been used to model the impacts of the European Union's chemical regulatory program.[79]

Regularly update evaluation frameworks and policies

Once assessment tools and decision-making policies are implemented aimed at realizing and maximizing the net benefits of battery energy storage deployment, the effects of these assessment tools and policies must be continually monitored and evaluated on whether they are achieving their intended purpose and whether they had any undesirable and unintended consequences. This means that to better maximize the net benefits of battery energy storage deployment, clear and standardized mechanisms need to be put in place to continually evaluate the effectiveness of implemented tools and policies against their intended goals and enable corrective actions to be taken if a policy is either not achieving its intended goal or producing unacceptable unintended consequences. Community-engaged participation could also provide empirical data on whether the tools policies are meeting their intended goals. Qualitative methods, such as interviews, public participation forums, and surveys would allow directly impacted stakeholders to provide empirical insight into assessment and policy implementation and effectiveness.

CONCLUSION

Significant barriers remain to developing an evaluation framework for sustainability to support decision-making related to rapid scaling of battery production and deployment. Here we suggest steps to overcome them to better ensure that stakeholder decisions meet sustainability goals while minimizing negative environmental and social impacts of rapidly scaling battery supply chains, manufacturing, and recycling capabilities. The main barriers to better utilizing these assessment approaches are found in the areas of data quality and availability underlying LCA-based sustainability assessment methods which limit their usefulness in decision-making processes.

First, developing the capability to track how decisions made by various stakeholders across the battery life cycle, from product designs to developing supply chain relationships, translate to environmental and social impacts. This need can be addressed by (1) setting up an expert community for promoting open-access, centrally available, and standardized data for battery energy storage life cycle inventories, (2) developing and refining impact assessment methods with better spatial and temporal resolution, (3) integrating energy system models with LCA, and (4) incorporating and refining social LCA tools.

Second, sustainability assessment approaches need rigorous and systematic mechanisms for incorporating the results into evaluation and decision-making processes for multiple different stakeholders. This need can be addressed by (1) developing and validating decision-support methods and tools specific to battery energy storage, (2) encouraging the provision of certain battery technology or assessment result data by battery developers or manufacturers to decision makers, and (3) formally establishing policies for the use of decision-support methods and tools in organizational decision-making processes.

Historical examples of other technology deployments have shown that there is always the potential for unintended environmental and social impacts, even when such deployments were aimed at addressing other types of environmental problems. Improving our ability to track and understand how stakeholder decisions influence environmental and social outcomes could significantly reduce the probability and extent of potential negative consequences of battery deployment at the speed and scale described in deep decarbonization scenarios. Building such a capability is a timely priority, since most of the battery capacity required for the clean energy transition has not yet been produced, meaning that we are at a critical juncture for ensuring that decisions made carry out large-scale battery deployment avoid negative impacts at scale. As can be seen by the example of the new EU Battery Regulation, policy and regulation is a key for pushing toward more sustainable battery value chains, but requires the corresponding evidences and a well-established methodological framework for setting a level playing field. The present paper identifies the main barriers in this regard and suggests approaches for overcoming them.

Limitations of the study

This perspective is based on the synthesis and analysis of perspectives contributed both by existing literature and policy and by the attendees who participated in the battery energy storage workshops hosted by the University of California-based authors. Participation in these workshops mostly consisted of attendees from the US and the EU; therefore, many of the points raised in this perspective may not adequately capture the on-the-ground conditions and perspectives of entities and populations from other regions which may also be involved in different aspects of the battery supply chain. We recommend that for future work, perspectives from outside the US and EU be more actively engaged. Additionally, this perspective is based on the literature and policy status as of the time of writing. As these aspects are continually being further developed, emerging and near-future literature and policies may shortly address some of the knowledge gaps highlighted here.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109898.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no conflict of interest.

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