JOURNAL OF THE AIR & WASTE MANAGEMENT ASSOCIATION
2022, VOL. 72, NO. 10, 1053–1062
https://doi.org/10.1080/10962247.2022.2118473

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2022 CRITICAL REVIEW DISCUSSION

Circular economy for lithium-ion batteries and photovoltaic modules—status, challenges, and opportunities

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Introduction

The 2022 Critical Review (CR) by Heath et al. (2022) used a comprehensive compilation of literature to assess how photovoltaic modules (PVs) and lithium ion batteries (LIBs) align with the principles and processes of a circular economy (CE). The authors meticulously document the current state of this alignment and identify knowledge gaps and future research needs. Herein, expert discussants provide additional perspectives and information on the topic. The discussants were generally complimentary of the CR and focused their comments on expanding the topics raised in or missing from the CR and steps needed to more fully realize a CE for PVs and LIBs in the United States. The discussants' appearances as coauthors do not necessarily indicate their agreement with the opinions of other discussants.

Gerald Braun: toward a more circular renewable energy economy

Renewable energy enjoys public support because it is key to climate change mitigation and long-term energy security. As renewable energy industries continue to expand, they will innovate and apply circularity strategies that can be adapted to other sectors. A general CE vision has evolved over decades, based on the accumulated experience of commercial enterprises (C2C-Center 2022a; C2C-Center 2022b). The fact that lead from "dead" car batteries is recovered and reused can be seen as validation of the CE vision.

The renewable energy industry has also been an early adopter of CE principles. For example, in 2005, First Solar implemented a prefunded collection and recycling program for cadmium telluride solar PV panels for large "behind the fence" projects (Field 2018). That same year, California banned LIBs from the regular trash stream while requiring some retailers to provide a battery-return option (Rishchar 2020). This ban facilitates circularity when the collected LIBs are recycled or repurposed; for example, end-of-life LIBs from electric vehicles can be reused and paired with solar PV installations (Pyper 2020). Silicon solar PV panels remain productive for decades, are warrantied accordingly, and are sometimes reused and repurposed. In 2021, California reclassified solar panels from hazardous to universal waste (Rishchar 2020), which is a less stringent hazardous waste classification with streamlined handling and reporting requirements that reduces management burdens and facilitates recycling.

"Cradle to cradle" (C2C) certification programs are now available to retailers, designers, and manufacturers, including those in solar PV and other renewable energy industries (C2C-Center 2014, 2022c). Integration of renewable sources with existing and new energy transport infrastructure is essential to affordability, environmental stewardship, and adoption rates. Integration of renewable energy product supply and recovery chains will have comparable long-term benefits and therefore merits near-term policy and industry attention.

The CR applies a conceptual CE framework to solar PV and LIBs and provides a comprehensive inventory of research literature and public domain documents. It also provides a window on renewable circularity research and practices to date and can be used to target future research, development, and demonstration projects that fill data and analysis gaps. An important next step is to develop a multiyear national plan that catalyzes circularity in the global renewable energy industry. The plan should identify a preferred vision, key success factors, enforceable obligations, and national, state, and local roles and responsibilities.

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/10962247.2022.2118473

For example, the preferred vision might be to not only to circularize material flows but to extend the expected life of renewable energy equipment and projects, thus multiplying decarbonization benefits and avoiding congestion on circular pathways. Key success factors might include global standards, enforceable obligations, state and national certification requirements, and research collaboration between industries, companies, and national laboratories.

A national renewable CE plan can illuminate aspects of the current situation, trends, and opportunities and lay out strategies identifying impediments, transitions, and core principles. Currently, most of the three million solar PV systems deployed in the United States are relatively small and in the early stages of their life cycle. They tend to be single-source systems, since electricity markets value bulk energy, not source flexibility and resilience. Integration of electric vehicle batteries with on-site solar PV systems lags as does storage-paired solar and wind in general.

States set standards for recycling and diversion of specific types of material, and solar PVs and LIBs are good candidates for such standards. These standards apply to local governments that provide waste collection and recycling services. In addition, some local governments facilitate land use circularity by making brownfield sites available for renewable energy projects.

Some current trends complicate planning for circularity. First, while PV panel and LIB manufacturing relies on familiar bulk materials, the range of materials in use will expand as panels and batteries are designed to meet new market requirements. Second, the solar PV market continues to diversify as it grows. Solar PV panels are mounted on rooftops, parking structures, unshaded brownfields and abandoned agricultural land, the sides of new buildings, and even on floating arrays on lakes and ponds. Last, project and equipment ownership and industry changes often occur before repairs, replacement, and decommissioning are required. For example, PV panels last much longer than some of the companies that make them.

Meanwhile, the growth and diversity of the renewable electricity sector create opportunities. The large, expanding, and stable market for equipment enables the United States to influence global industry practices and helps drive economies of manufacturing scale and CE principles. Renewable equipment distribution networks supported by high-volume manufacturers can also serve as product recovery and repurposing networks.

In light of the current situation and trends, a national renewable CE plan should anticipate ever-improving economic integration of solar PVs and LIBs. It should also identify and enforce project decommissioning, equipment disposition, and site restoration obligations consistent with circularity. There are significant information gaps impeding the creation of a CE for PVs and LIBs. Research and development is needed, first to fill data and analysis gaps, evaluate trade-offs, and pilot commercial circularity choices, and second, to learn from and distribute experience from successful ongoing solar PV and LIB industry C2C programs and C2C-certified companies.

There are numerous impediments to a circular renewable energy economy, including subsidized and tax-incentivized project financing that leads to ownership changes that make equipment warranties more costly to enforce. In fact, at the current stage of the clean energy transition, all types and sizes of PV systems last longer than they are likely to remain under the control of the original owner. At some point, this may also be true for LIB storage systems. Also, the chain of responsibility for renewable energy system stewardship is more easily disrupted for smaller on-site and community renewable projects where longer-term obligations are harder and more costly to enforce. Another impediment is that in the United States renewable electricity deployment depends primarily on imported equipment, resulting in long circular pathways, problematic enforcement of agreements, and lack of visibility to manufacturer decisions impacting circularity. Last, solar and battery project finance models discount the value of long, trouble-free inverter and battery life.

Increased integration of solar PVs, wind, battery storage, solar thermal power, and thermal storage into the U.S. energy generation sector will result in more cost-efficient resilience and decarbonization and will open wider economic windows for circularity investments. In parallel, as the renewable electricity economy continues to expand, a renewable gas economy will likely emerge, will synergize with the renewable electricity economy, and will require circular pathways for fuel cells and electrolyzers. Renewable gas deployment is currently organized around deeply carbon-negative projects that produce biogas or electricity for on-site use (e.g., at wastewater treatment plants) and projects that convert animal waste to pipeline quality bio-methane. Going forward, renewable hydrogen production and advanced incineration will economically enable the circular renewable electricity economy by meeting the need for affordable long-term storage.

A core principle underlying a national renewable CE strategy is that renewable energy circularity costs will be minimized if batteries, fuel cells, and electrolyzers evolve to have longer trouble-free operating lives. Once circular pathways are open, costs of recovering materials and equipment from abandoned or decommissioned renewable energy projects must be documented and reduced to be affordable, and obligations of equipment owners must be clear. These principles should be considered, amended, and supplemented as a national multiyear renewable CE plan takes shape. Annual progress assessments can inform plan updates while identifying opportunities for increased circularity and elimination of technological, economic, and political roadblocks.

Stephanie L. Shaw: CE principles in the electric power industry

Electric power companies have demonstrated commitment to CE concepts for many energy technologies over the years by exploring sustainability benchmarking metrics; undertaking facility life extension steps; redeveloping decommissioned thermal generation sites for renewable generation deployments; adjusting coal generation practices to ensure coal combustion product quality can support beneficial use in secondary markets; and building on investment recovery practices to constructively liquidate materials by reusing or recycling renewable generation and energy storage assets that have reached the end of their first operational life. EPRI is an independent, nonprofit research organization that advances safe, reliable, affordable, equitable, and clean energy for society. EPRI has been actively supporting the electric power industry's implementation of CE principles through research programs related to environmental issues across the life cycles of wind turbines, solar photovoltaics, and energy storage (EPRI 2021a).

Several roles are played by electric power companies in CEs (EPRI 2021b). First is as a producer of electricity. Renewable generation and use of energy storage reduce a variety of climate and environmental impacts by the electric sector, as well as all other economic sectors using grid electricity, and play important roles in supporting the grid. Services, technologies, and guidance are provided by electric power companies to customers so energy efficiency can be broadly improved. The second role is as a purchaser. Electric power companies are responsible for sourcing of electricity and a wide variety of equipment, material, and services for which they have the chance to keep CE principles in mind. Purchasers and engineers may prioritize selection of equipment or facilities designed for reuse or recycle during the design and procurement phase. Finally, as asset managers, electric power companies are responsible for maintenance and life extension through repair and refurbishment; safe and compliant final disposition, whether in the form of reuse, recycling, or disposal; and investment recovery when materials reach the end of their useful lives.

EPRI worked with the Anthesis Group to develop an electric power industry-specific CE framework (EPRI 2021c). The top-tier objectives were reducing natural resource use, extending equipment life, and eliminating resource loss, and implementation steps were suggested for each. Case studies have documented that successful operationalization of CE principles for renewables and batteries in electric power business strategies have also been developed (EPRI 2021d). These include items such as (1) successful peer engagement across multiple departments (e.g., integrated planning, design, procurement, engineering, construction, crews, environmental compliance, waste management, investment recovery, legal, risk management, communications, and employee development/training) to eliminate issues early in technology life cycles; (2) effective use of skills training, personal employee goals, and corporate communications to align staff on addressing waste reduction goals; (3) educating suppliers and vendors on opportunities associated with CE principles and requiring their adherence to relevant product metrics; and (4) publicly sharing goals and results such as environmental life-cycle assessment insights or circularity scores to enhance transparency and alignment.

Assessments of supply chain (EPRI 2021e, 2022a) and end-of-life management aspects for renewables and energy storage technologies have also been thoroughly investigated (EPRI 2022b). These include supply chain risks and environmental and social issues, as well as opportunities to improve supply chain resiliency. Guidelines and best practices for approaching renewable and energy storage procurement, as well as planning and logistics for decommissioning and recycling PVs, wind turbine blades, and LIB modules, have been created for electric power companies and their value chain partners. Investigations into the feasibility and needs for PV and battery module reuse and repurposing are also ongoing.

A particular strength of the CR was the high level of detail brought to assessing the numerous aspects of and wide range of complexities influencing the circularity of PVs and LIBs. This allowed the review to detect and highlight often overlooked aspects, such as the fact that recycling of LIB components beyond cathode material (e.g., graphite) and balance of system components in packs, modules, and systems provide additional circularity opportunities. Based on weight breakdowns of stationary battery energy storage-system components, the total costs of dismantling, transporting, and recycling the battery modules are estimated to be only 68% of the total decommissioning costs of the system. Other materials possible to recycle include the system container housing (e.g., steel or concrete), wiring and cable materials, racking and equipment housing (e.g., scrap metal), power and communications electronics, cooling system fluids, transformer oils, and fire suppression agents (EPRI 2017, 2022c).

Another strength of the CR is the recognition of the role of customers, who can be varied depending on the ownership model (e.g., direct ownership by a utility, commercial, or residential entity or ownership by a commercial or financial entity with generation or storage services provided to a customer through a product-service model). While forward-thinking suppliers are helping push the industry in the right direction, an end user's sustainability objectives are necessary to accelerate the process (EPRI 2021f; Powicki, Li, and Libby 2022). If environmental, social, and governance considerations are given substantial influence during procurement, this could favor compliant suppliers over lower-cost options. Thus, procurement and sourcing guidelines, as well as company material-acquisition policies, can help speed the path to commercially available sustainable technology designs.

One important knowledge gap in the CR is the economic value of circularity. While mention is made of the need for cost information related to recycling, an additional focus on quantitative assessment of benefits and costs of implementation of circularity principles in the business strategies and technical operations of entities across the value chain is an area in which the entire field of study could benefit. Research suggests that end-of-life financial obligations are not yet fully accounted for by vendors, integrators, or customers despite their increased awareness and the fact that local to federal policies and regulations regarding reuse, repurposing, recycling, and related activities are under consideration (e.g., EPRI 2020a, 2021f, 2021g, 2021i). Such economic assessments are needed to inform decision-making processes at many levels (such as policy and regulatory actions by governments and other bodies; investment decisions; and operational choices by technology manufacturers, owners/operators, and waste and material management companies) and would help to prioritize actions driving circularity. The motivation to support recycling, reuse, and holistic environmental and social assessments that identify and reduce externalities exists in many entities due to their environmental and natural resource stewardship and corporate social responsibility priorities. However, implementation requires resources. Improved understanding of which circularity actions create a positive return on investment, which are comparatively low cost, and which will require concerted financial prioritization will serve to spur early action and speed implementation. Such economic analyses are also important to inform discussions with public stakeholders and support the social decision-making processes.

Although not in the scope of the CR there also exists opportunities for circular management of wind turbines and blades. The large size, weight, and volumetric projections of turbine blades in particular suggest they are an important resource if they can be reused (EPRI 2021h). In terms of weight, wind farms primarily consist of concrete, which can be recycled but faces technical and value challenges (Mamirov, Hu, and Cavalline 2022), and steel, which is widely recycled and has moderate value. It is the turbine blades and nacelles (i.e., turbine housing) that currently have minimal clear and economical recycling options. Blades and nacelles are primarily made of composite materials such as reinforcing fibers (e.g., glass and carbon fiber) and thermoset resins and adhesives that represent a large fraction of the material value but are less recyclable than homogeneous materials. Fillers such as balsa and foams are also used. Blade recycling is active area of research and development, with grinding and reuse, co-processing in cement clinker production, and pyrolysis to recover fibers for reuse currently under investigation as alternatives to landfilling. A challenge that must be addressed is that current recycling approaches result in a downgrading of the quality and value of recovered fibers and resins, which limits opportunities for the use of those materials in new products (EPRI 2020b).

A final consideration is the use of second-life PVs and LIBs by developing countries. There is a need to track materials exported to other countries for reuse or repurpose to understand the potential impacts throughout their full life cycles. Informal waste management is common for energy technologies in developing countries. This has the potential to become an environmental justice issue if all the second-life modules (perhaps with questionable certification for their repair and/or refurbishment) are sent to developing countries that must then deal with end-of-life management, perhaps without the appropriate resources or infrastructure to maintain safety and environmental control (Tetra Tech, 2021). Export to developing countries for any use should reflect United Nations Sustainable Development Goals, such as Goal 12: Sustainable Production and Consumption (United Nations 2015).

In the last five years, the renewable generation, LIB, and electricity industries have moved quickly to begin addressing concepts of circularity through the development of corporate policies and enhancement of supply chain and end-of-life material management opportunities. Increased focus on these topics will continue as the industries mature and as utilities gain more experience owning, operating, and maintaining these resources (EPRI 2021e, 2021f, 2022a; Powicki, Li, and Libby 2022). Widespread recognition exists that embedding CE concepts into business strategies can be a market differentiator. Relevant information requests are beginning to be incorporated into customer requests for proposals on new facilities and equipment and other procurement actions (EPRI 2021d, 2021g). A shift toward a "design for reuse, repurpose, or recycling" philosophy by component vendors and equipment integrators, while retaining cost, reliability, and durability optimizations, is an important next step that should be supported (Powicki, Li, and Libby 2022). The effectiveness of government–industry partnerships and research and development collaborations will influence when and where the needed technologies, infrastructure, policies, and markets emerge.

Brian Tarroja: CE decision support system needs

The insights of the CR brought forth two key questions to identify and gain support for measures that promote better alignment of PVs and LIBs with CE principles:

(1) How do we assess the circularity of a clean energy technology's life cycle?
(2) How do we systematically track whether decisions improve or reduce a technology's alignment with CE principles?

These are questions that researchers and assessment tools used to inform decision-making will need to address. Whether it is a policymaker designing policies or standards to implement for the PV and LIB supply chain or manufacturers interested in changing the set of materials used in their products, decision makers will need clear information on how their options contribute to or detract from alignment with CE principles. Further, the extent to which these options contribute to circularity needs to be elucidated to justify their costs and/or to gain political or social support for such measures.

Building an assessment framework that can address these questions requires tackling more-specific questions. What are the metrics that should be chosen to represent better alignment with CE principles? What methods and data are needed to meaningfully calculate these metrics? How do we ensure that information from assessments that calculate the performance of a product's life cycle on these metrics is relevant for decision makers?

These are complex questions without definitive answers. Following are some of the key challenges for building a systematic framework for tracking the circularity of PVs and LIBs and a discussion of some potential solutions. These are organized into three themes: data needs, assessment needs, and implementation into decision support systems.

The first step for assessing and tracking the circularity of PVs and LIBs is obtaining data that characterize how a product's life cycle aligns with CE principles. This consists of physical data on material and energy flows and nonphysical data that characterize the effects of and feedbacks for the product's life cycle to economic, sociopolitical, and human health influences. For physical data, life-cycle inventories (LCIs) refer to data that account for the materials and energy inputs and outputs associated with the processes involved in extracting materials, manufacturing, use, and end-of-life of a given product. PVs and LIBs each encompass a wide variety of products differentiated by their chemistry and material sets, resulting in differences in performance and environmental impacts. As discussed in the CR LCIs are available for variations of PVs and LIBs, but obstacles remain.

First, many existing LCIs are not standardized and are not regularly updated to reflect the latest state of technological performance or supply chain configurations. LIBs, for example, have improved significantly over the past decade in terms of their energy density (Muralidharan et al. 2022) and life cycle as new chemistries reached commercial scale or existing chemistries were improved. Changes in supply chain configurations are also taking place with a shift toward battery chemistries that use less or no cobalt, due in part to the recognition of the contribution of cobalt demand to exacerbating child labor issues in the Congo (Amnesty 2017). If LCIs do not reflect up-to-date developments in a product's life cycle, they may mischaracterize its performance relative to other products.

A potential solution to this obstacle is to develop and implement standards for reevaluating and composing LCIs for existing and emerging PV and LIB technologies at regular intervals. Data often come from entities that want to protect their competitive advantage, so a process for battery suppliers and manufacturers to provide data on their products anonymously would be needed. Additionally, minimum standards for the content and quality of LCIs should be established, allowing for comparative assessments that inform decision-making.

Second, nonphysical data should be required for assessments to track impacts beyond the material and energy flows on the environment, and much of these data will be in the form of narratives that cannot be easily input into models or technical calculations. Collecting and using these data requires interdisciplinary expertise and tracking or attributing the effects of the physical aspects of a product's life cycle across multiple jurisdictions and domains, some of which may not have accessible or reliable records.

Some potential solutions to this obstacle can include retrospective policy analyses to characterize what types of policies have performed well in implementing CE-aligned practices and the economic/sociopolitical conditions that enabled them to do so. Investment in developing datasets with the spatial and demographic resolution necessary to track distributional effects and more specifically predict the distribution of benefits or impacts of a decision to change a product's life cycle would also be helpful. Developing such datasets will require engaging with communities that have been negatively affected by previous policies to understand on-the-ground impacts and narratives. These engagements must be careful to avoid academic extractivism and be aimed at bringing tangible benefits to these communities as a result of their participation.

The next step is to develop frameworks and tools that use physical and nonphysical data to track how well a product's life cycle aligns with CE principles. This alignment cannot be condensed into a single metric, since CE encompasses a set of strategies, i.e., Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover, listed in descending order of priority. Therefore, each CE strategy will require a metric to track how well a configuration of a PV's or LIB's life cycle performs within each strategy, as well as a weighting of the strategy's relative priority.

Some strategies are better characterized by metrics based on physical principles; for example, performance in the Recycle strategy can be measured by the percentage of material mass recycled for PVs and LIBs that reach their end of life, or performance in the Reduce strategy can be measured by the material use intensity per functional unit. Other strategies will be better characterized by metrics that track how a product's life cycle performs relative to other potential performances in that strategy. For example, performance in the Rethink strategy can be based on how many simultaneous applications for which a battery can be used (e.g., backup power, renewable energy shifting, power quality, etc.) or for a solar photovoltaic panel (e.g., electricity production, shade for cooling, harvesting waste heat, etc.).

Weighting the different strategies based on their priority will also be important. The CR documented that PV and LIB literature is disproportionately focused on recycling, the CE strategy with the second-lowest priority. Steps that improve a battery's performance in the Reduce strategy by reducing critical material intensity, for example, should be considered to have a higher contribution toward alignment with CE principles.

Finally, it is important to recognize that methods already exist that are aimed at or can be used to assess aspects of circularity, including but not limited to environmental and social life-cycle assessment (Life Cycle Initiative 2022; Walzberg et al. 2021), human health assessment, material flow analysis, and multicriteria decision-making. New methods may need to be developed, but developing a framework to systematically assess circularity depends on leveraging existing tools into a workflow that can address questions of progress toward or away from circularity and development of new tools as needed to fill in knowledge gaps in that context.

Once a working framework for tracking the circularity of PVs and LIBs is established, the information needs to be made actionable by decision makers. In this case, a decision maker is any entity tasked with making a decision that affects the configuration and performance of the PV and LIB life cycle. This includes but is not limited to policymakers, regulatory agencies, manufacturers, material or component suppliers, and local community governments.

A first step to accomplish this is to regionalize the assessment metric outputs. Tools such as life-cycle assessment produce indicators for different types of environmental impacts, but these indicators do not always map to the metrics that are used by decision makers for tracking impacts in their jurisdiction. For example, a life-cycle assessment may indicate air pollutant emissions from the life cycle of a LIB, but these may be aggregated over a very large spatial scale (e.g., country) and may be difficult to translate to air pollution impacts at a smaller scale where regulatory agencies (e.g., air districts in California) operate. Additionally, when an assessment identifies environmental impacts, it is not always clear how these impacts are distributed among demographics within a given region, which may be a driving factor in the development of regulations. Therefore, more-robust practices for translating the outputs of assessment tools to metrics that decision makers use or have jurisdiction over will be beneficial.

A second step is to ensure that assessments provide information on various sensitivities and inform a range of potential decisions. Leveraging the assessment of circularity for decision support should involve determining the potential benefits and limitations of proposed decisions by comparing options and including the effects of uncertainty. It is more informative for decision makers to understand how a design space behaves rather than fixating only on optimal outcomes.

Finally, decision-making can be improved by monitoring and verification of CE contributions and associated co-benefits. When policies or design decisions are made to improve the circularity of PVs and LIBs, the effects of these decisions in the context of alignment with CE principles should be monitored after implementation and compared against the projected benefits and impacts from the assessment that motived them. If there is a deviation from the projections in practice or if there are unintended negative impacts in whole or for specific demographics, then driving factors must be determined and the assessment framework updated to better reflect them. Information provided from on-the-ground monitoring will be important for ensuring that circularity assessment tools can continually produce relevant information to guide decision-making.

Chih C. Chao: integrated approach for achieving a PV and LIB circular economy

To work toward a CE, a fundamental change in producer and consumer mind-sets is needed. Specifically, waste needs to be viewed as a misallocated resource, and the concept of waste management must shift to one of resource management. As one goal of a CE is zero waste to landfill, then far more aggressive recycling and reuse of materials is needed. By-products of the production and consumption of goods often contain a mix of components, hindering their use. A series of operations, including sorting, separation, purification, upgrading, and/or remanufacturing, is required. The regenerated products can then be put into the market for use. This recycling framework would involve a network of waste or secondary resource collection, processing, regeneration, and product distribution. In addition, a broad set of stakeholders, including producers, consumers, collectors, recyclers, governments, the research sector, and financing institutions, needs to be engaged early in the process.

Achieving higher goals of zero waste from production to consumption and, ultimately, zero waste generation entirely, will require further fundamental changes in thinking and way of life:

- Change the economic drivers from unlimited use of resources to "doing more with less" by revisiting the production and consumption processes to continually make them more efficient with less material and energy use while achieving an equivalent or higher functionality.
- Change life patterns from wasteful to green consumption through education to be material, energy, and safety conscious when purchasing needed products or services.
- Re-orient environmental management practices from passive protection to proactive conservation by restructuring the system to adopt a resource conservation approach instead of the conventional end-of-pipe protection practice.

An index for evaluating and communicating the sustainability of a proposed CE, including its economic viability and environmental soundness, is needed. One such index is Green Competitiveness, which is the ratio of the total value of the products and services generated by the CE divided by the summation of the impacts that the subject system imposes on the environment. Depending on the characteristics of the targeted CE and the priority concerns of the stakeholders, the indicators of the environmental impact will differ but could be based on material consumption, water usage, energy use, CO_2 emissions, and toxicity accumulation, for example. In a viable CE, the value of the numerator is expected to become higher than that of the existing system of production, while the value of the denominator is expected to be lower than the current system, hence increasing green competitiveness.

The implementation of a CE is a multifaceted endeavor requiring a number of political, industrial, social, and market conditions. A sufficient set of conditions for achieving CE goals includes

- coherent governmental regulations and permitting requirements,
- clear definitions of what constitutes waste versus recyclable resources,
- standards and certification systems for recycled products,
- market acceptability of recycled products,
- achieving economies of scale for resource recovery,
- mechanisms to finance innovators for start-ups,
- incentives for zero-waste participants and programs, and
- technology breakthroughs for creating added value for recycled products.

The development of a CE system is an industrial or regional effort requiring the involvement of stakeholders to work as a team, to collectively

- resolve the legal and administrative issues of shifting from waste disposal to CE systems,
- select a champion region(s) and demonstrate the feasibility of developing and operating zero-waste systems,

- educate the public about how individuals can participate effectively in sorting, separating, collecting, and delivering waste and recyclables to designated locations, and
- align multiple resources in science and technology research, as well as venture capital, to accelerate the necessary innovations to business practices.

The widespread implementation of CEs remains a goal (Chao et al. 2017); however, economies around the world are making substantial progress toward achieving the first step of zero waste to landfill. The supplemental material discusses successful efforts in Taiwan (Chao 2017), the Netherlands (Houng 2016), and the City of Edmonton, Alberta, Canada (McConnell 2019).

Status of PV and LIB circular economy

A review of LIB recycling practices (Heath et al. 2022; Islam et al. 2022; Niese et al. 2020; Robertson 2021) reveals that recyclers are focused on recovering lithium, cobalt, nickel, and manganese from waste LIB. China has the largest and longest-in-service LIB recycling companies, due to China's mandate imposing extended producer responsibility (EPR) on the electric vehicle industry. This has resulted in relatively strong recycling of LIBs, particularly those made from nickel-cobalt-manganese (NCM) and nickel-cobalt-aluminum (NCA) chemistries. This contrasts with North America, where LIB recycling is not widely practiced. This is due to multiple barriers, including the lack of clear governmental regulations to enforce or encourage recycling; low landfill costs discouraging recycling efforts; high cost of waste LIB collection and transportation; complexity in handling waste LIBs of different cell chemistries; lack of coordinated value chain partnerships aiming for industrial symbiosis; limited scales of economy; and insufficient value addition efforts to make recycling profitable.

PVs contain valuable materials such as silicon, silver, aluminum, copper, and gallium and hazardous materials such as lead and cadmium that can be recovered by recycling (ARUP 2022; Farrell et al. 2020; Heath et al. 2022). Furthermore, PV module production is an energy-intensive process involving the production of PV-grade Si material. The production of one tonne of PV-Si material emits on average about 100 tonnes of CO_2, requiring innovative technologies to reduce the CO_2 emissions. However, on a life-cycle basis, PV is comparable to other renewable electricity technologies and far less than fossil fuel-generated electricity (NREL 2022).

Recycling waste PVs to pure-grade materials will reduce PV life-cycle carbon emissions as well as add significant value to recycled products. PV recycling is not currently widely practiced due to many of the same barriers hindering LIB recycling. The European Union is embarking on PV recycling programs and has implemented the Waste Electric and Electronic Equipment (WEEE) Directives, Producer Responsibility Law, and German Circular Economy Act to provide a sound basis for the PV recycling industry.

To overcome the barriers and advance the opportunities for achieving the PV and LIB CEs, an integrated approach is suggested, based on a strong government–industry–academia–community partnership as follows:

- Enact regulations to mandate or encourage PV and LIB CE actions.
- Form PV and LIB CE alliances that facilitate industrial symbiosis.
- Align science and technology resources and venture capitals to accelerate the innovation-to-business process.
- Promote low-carbon-intensity PV and LIB production.
- Focus on value addition to recycled products.
- Embark on practical CE business models.
- Provide incentives for CE participants and programs.
- Establish standards and certification systems for recycled products.

Disclosure statement

The assumptions, findings, conclusions, judgments, and views presented herein are those of the authors and should not be interpreted as necessarily representing their institutions' policies.

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