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Review:

Defining Requirements on Technology Systems Assessment from Life Cycle Perspectives: Cases on Recycling of Photovoltaic and Secondary Batteries

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Since the enactment of the "Feed-in Tariff" scheme in 2012, the solar power generation capacity in Japan has been steadily growing. Therefore, in the near future, the demand for the mass processing of spent photovoltaic (PV) panels is expected to increase. Secondary batteries, especially lithium-ion batteries (LiBs), have become important products for vehicles and mobile devices. The production of LiBs is also expected to significantly increase in the near future. In this study, we address the design of recycling systems for such emerging technologies. From life cycle perspectives, the requirements for the assessment of these technology systems are carefully defined through a bibliometric analysis of technology assessments, critical reviews of current research and developments in the recycling of PV panels and LiBs, and analysis of the intensities of life cycle impacts (such as greenhouse gas emissions and resource use). The necessities for life cycle assessments, material flow analyses, and other assessment methods are clarified, along with the conditions to be examined using these assessment methods.

Keywords: bibliometric analysis, requirement definition, life cycle assessment

1. Introduction

Japan's energy policy has expanded the use of renewable energy, including solar power. Photovoltaic (PV) technology is firmly expected to provide a fundamental contribution to the transition from traditional fossil fuels to renewable energy-based economies [1, 2]. PV application in Japan has increased rapidly in the last 20 years [3], with the expansion increasing even further since the Feed-in Tariff scheme was instituted in 2012 [4]. By approximately 2025, significant numbers of PV panels could reach their end of life (EoL). In particular, PV installations started near the end of the 1990s, and the average lifetime of a PV panel is approximately 25 years; thus, the EoL of these panels will lead to large amounts of waste [5]. In energy-creation technologies such as PV systems, secondary batteries have also been required in various products (in particular, vehicles and mobile devices), and their waste is also expected to increase considerably in the future [6].

When designing target recycling systems, the optimal mixture of physical segregation and chemical treatment(s) should be pursued, considering the specific characteristics of the respective components. For example, the components of PV panels [7] have specific characteristics in terms of the economic and environmental impacts of the product life cycle. Tempered flat glass induces relatively greater environmental impacts among glass types, and can be reused or recycled as glass if it is separated from the other materials. Metals such as copper, silver, and rare metals are economically valuable. Thus, they are already considered as targets of recovery, whereas glass should be removed from the inputs to the metal recovery processes. Crystalline silicon is another potential material for recovery, as its production requires high energy consumption; however, it is often contaminated with other metals inside PV cells.

Furthermore, the design should account for the entire value chain. However, sufficient data remains lacking, especially for the post-consumer life cycle stages, i.e., the physical segregation and chemical treatment processes and associated environmental impacts should be characterized. In this study, a life cycle assessment (LCA) was conducted on conventional and proposed recycling systems for spent PV panels and secondary batteries. The current disposal system for spent secondary batteries still relies on landfills without effective recycling of valuable and hazardous metals, thereby presenting a major environmental and human health risk. The planning of strategic EoL management can not only mitigate the environmental impacts, but can also avoid shortages of critical materials needed to meet future resource demands [8]. Therefore, in preparation for the mass processing of spent

PV panels and secondary batteries in the near future, the reuse/recycling and disposal schemes thereof should be discussed.

In this study, we extract the characteristics of applicable recycling technologies for spent PV panels and secondary batteries (in particular, lithium-ion batteries (LiBs)) by reviewing the existing literature, as the possible options for these devices have become massive. To address the transitions of recycling systems from existing (conventional) approaches to preferable ones, systems must be designed based on adequate assessments of possible technology options. To extract the assessment settings required for such technology assessments (and ultimately social implementation), the existing technology assessments are structured through a bibliometric analysis as a data-driven approach, and from the viewpoints of the interrelations among the social, economic, and technological aspects. In addition, the existing technologies and system options for managing spent PV panels and LiBs are critically reviewed from the viewpoints of cost, environmental impact, and resource efficiency. The literature are selected based on times cited, i.e., an empirical indicator of their importance. Furthermore, the recycling effects on products are examined, and the environmental load intensities are calculated by a LCA based on a life cycle inventory (LCI) database. By considering the pros and cons of technology options through these assessment reviews, the requirements to be addressed in technology assessments of options for the EoL management of spent PV panels and LiBs are defined.

2. Materials and Methods

2.1. Requirement Definition of Technology Assessment

A technology assessment should be conducted to clarify the multiple aspects of target technologies and systems, and to examine their performance after social implementation. In this study, the requirements for the assessment should address the issues occurring in the life cycle of waste, which has different flows of cash and materials relative to product supply chains.

In this study, based on the results obtained from systematic reviews and intensity analyses, the requirements for technology assessments of the options for managing the EoLs of spent PV panels and LiBs were extracted and defined. A bibliometric analysis can generally indicate the data-driven requirements for technology assessments directed towards social implementation (e.g., the key points of issues are organized). Critical reviews of the applicable technology options and case studies in technology assessments for the recycling systems of PV panels and LiBs can be used to structure expert judgments regarding their recycling. The intensities of producer prices, environmental impacts, and market sizes can facilitate a quantitative prioritization to support the design of recycling systems. Accordingly, we conducted these three analyses to review the general issues on technology assessments, i.e., by bibliometric analysis, critical reviews of current specific discussions on PV and LiB recycling, and an intensity analysis to consider the potential contributions to life cycle impacts induced by avoiding additional production of PV panels and LiBs via recycling.

2.2. Systematic Review of Technology Assessment

2.2.1. Bibliometric Analysis of Technology Assessment

The elements of technology assessments that have been proposed for implementation include shifts in social systems, such as the relationships between the socio-, econo-, and techno-spheres through transformations in aviation systems [9], and regional transformations regarding the use of locally available resources [10]. The relationships between these areas have also been examined, particularly in studies related to biomass-derived production. The economic aspects of technology implementations have been examined in technoeconomic (TE) analyses aiming to clarify the relationships between the characteristics of technologies and various economic indicators, such as direct and indirect costs, fixed capital investments [11], and product prices [12]. A socioeconomic (SE) analysis has also become an essential method for analyzing the impacts of technology implementations on SE systems. Ji and Long summarized the current studies on the SE effects related to biofuels in terms of income, employment, food security, and economic cost by addressing not only feedstock, conversion, and opportunity costs, but also by addressing the loss in land value caused by pure energy crops [13]. The benefits should be analyzed within a sociotechnical (ST) approach to ensure that society benefits from the technology implementation. In small communities, the social aspects of renewable energy systems are essential [14], and their quantification can be partially conducted using contingent valuation methods, such as the willingness to pay [15]. ST research can provide broader feasibility checks on the outcomes of technologies [16].

To extract the functions required for the scientific analysis methods, a bibliometric citation analysis was conducted by applying an academic landscape system [17, 18]. This method was used previously in characterizations of sustainability [19], its assessment methods [20], energy security [21], distributed energy sources [22], and smart energy simulations [23]. A total of 94,459, 2,252, and 2,289 papers including the words "technoeconomic," "sociotechnical," and "socioeconomic" (in the abstract, title, or keywords), respectively, were retrieved from the Web of Science [24]. Clusters were created based on these citation networks, as discussed in a previous work [25]. Among the topics of the classified clusters, this study focuses on energy-related topics.

2.2.2. Critical Reviews on Photovoltaic (PV) and Lithium-Ion Battery (LiB) Recycling

A critical review, also known as critical analysis, represents an author's critical thoughts on the advantages and disadvantages of emerging technologies. Unlike a literature review, a critical review not only summarizes the information on technology developments in a field, but also evaluates the technical novelty, economic feasibility, and possible environmental benefits when implementing the emerging technologies in society.

Usually, the technical novelty is first confirmed via scientific experiments, which indicate whether a new technology can successfully and effectively transform the products at issue into the expected results. However, technically feasible technologies are not always suitable for upscaling into industrial processes; there might even be a high probability of serious environmental impacts. Thus, life cycle thinking, which aims to guide technology development without unnecessary time consumption and financial waste, is very important for the strategic assessment of an emerging technology. The key factors considered in life cycle thinking were assumed in this study to include the following items. 1) Systemic thinking substitutes an emerging technology into a current recycling system, to evaluate the compatibility with conventional technologies and potential impacts on overall material/energy flows in the system. 2) An economy of scale considers cost reductions and impact mitigation as important factors when scaling up a disposal capacity using an emerging technology. 3) An LCA analyzes and evaluates the overall resource consumption and environmental impacts for a product during the complete life process, i.e., from production to transportation, consumption, recycling, and final disposal.

2.3. Intensity Analysis of Life Cycle Assessment (LCA)

Product prioritization is a rational policy for effectively establishing recycling systems. The various aspects to be considered for recycling systems (such as the locations of stakeholders [26] and weight intensities) were examined in the context of producer prices, environmental impacts (i.e., climate change), resource depletion, an integrated single indicator, and market sizes of products (as retrieved from the LCI database and a national input and output table (IO table)).

The inventory database for environmental assessment (IDEA) v.2.3 [27] was used as the LCI database, from which cradle-to-gate LCIs were extracted for greenhouse gases (GHGs), consumed resources, and other available inventories for a life cycle impact assessment (LCIA). An LCIA method based on endpoint modeling (LIME) [28] was adopted for the LCIAs of climate change and resource usage, and the LIME index, an integrated indicator, was used to represent the life-cycle GHG emissions (LC-GHGs) [kg-CO_{2eq}], life cycle resource use [kg-Sb_{eq}], and LC-LIME index [JPY], respectively. The LCIs for the PV panels and LiBs were extracted from "ecoinvent" [7]

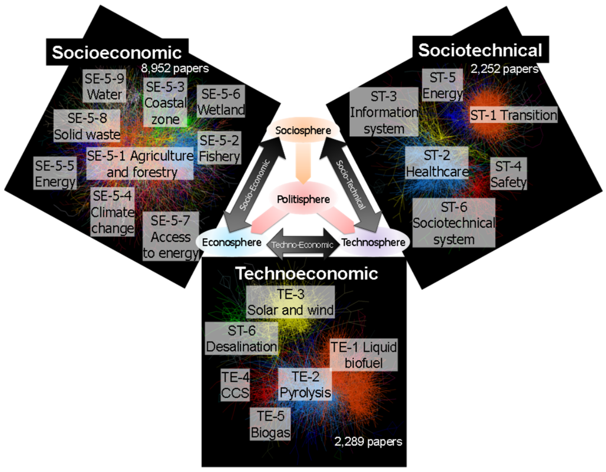

Fig. 1. Citation networks of journal articles including those on socioeconomic (SE), sociotechnical (ST), and technoeconomic (TE) aspects extracted from the Web of Science using the academic landscape system.

and other studies [29, 30]. The impact factors of the LCIAs for these LCIs were set as in LIME version 2. The weights of the products were defined as the summation of the raw materials input into their corresponding LCI databases. The product weights for the LiBs were obtained from literature [29].

The producers' prices and product market sizes were acquired from the IO tables [31]. The information regarding freezers, mobile phones, light and small passenger cars, PVs, and LiBs was limited, and was therefore extracted from other statistics [32], such as the installed capacities of PV systems, number of LiBs for cars, and sales amounts.

3. Results and Discussion

3.1. Academic Landscape

Figure 1 shows the citation networks obtained from journal articles including SE, ST, and TE issues, as extracted from the Web of Science using the academic landscape system. Whereas most of the clusters recognized in the SE sector include topics on health issues (see Appendix A1 for the clusters), SE-5 covers the SE aspects of ecosystems related to energy issues. SE-5 consists of 8,952 documents that include issues related to ecosystem services: agriculture, forestry, fisheries, coastal areas, climate change, wetlands, solid waste, water systems, and conservation areas. Among these, the energy issues are clustered in SE-5-5 and SE-5-7. When designing sustainable energy systems, multicriteria decision-making is urgently needed [33] and SE drivers are necessary, as has been discussed in the context of bioenergy projects [34]. A social LCIA has also been developed for quantifying social side effects in a life cycle [35]. Accessibility has also become an issue in the SE aspects of energy [36].

The clusters recognized by the ST area include the term

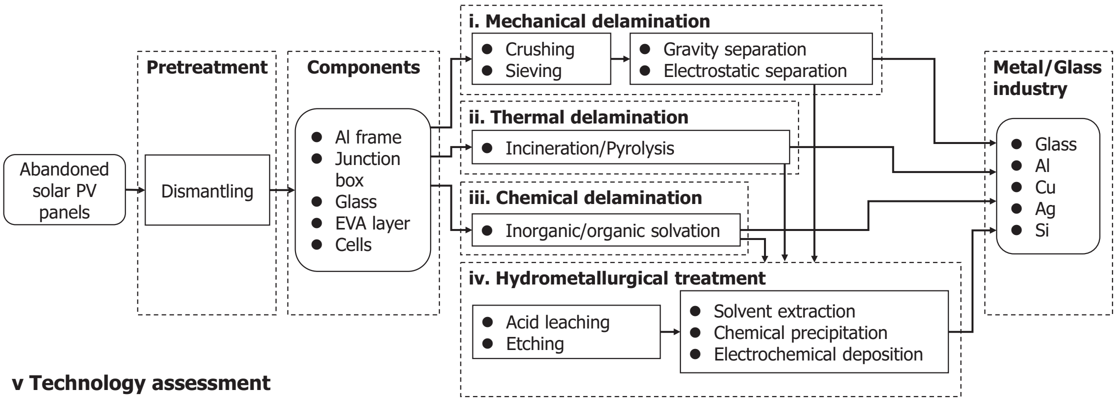

Fig. 2. Possible technology combinations for recycling abandoned solar PV panels with the contents of Subsection 3.2.1.

plus "transition" in their keywords (see Appendix A2). In ST-1, the largest cluster, the governance of sustainable ST transitions [37] is widely discussed, e.g., in regards to the translation between green niches and ST regimes [38] and the typology of pathways such as transformation, reconfiguration, technological substitution, dealignment, and realignment [39]. The ST approach is adopted in the analysis of other systematic implementations, e.g., patient care information systems and health care [40] in ST-2, broadband and mobile systems [41] in ST-3, and monitoring and management of safety systems with regard to organizational culture and core tasks [42] in ST-4 (using available online tools such as Wikipedia [43] and bots [44]). The energy issues are clustered in ST-5, where decarbonization requires an ST transition [16] to imaginary future systems, such as smart grids [45] and vehicle-to-grid integrated systems [46]. Thus, both policy-driven and narrative-based approaches are necessary [47] to construct a productive engagement [48] of people in local communities [49] and energy systems [50].

A large number of TE studies have explored energy-related topics (see Appendix A3). Cluster TE-1 covers the analysis of liquid biofuels, such as bioethanol from lignocellulosic materials [51] and aviation fuel from various feedstocks [52], including discussion of a hydrocarbon biorefinery [53]. Gaseous fuels are clustered in TE-5, including sourcing from biomass [54] and its utilization in fuel cells [55]. Pyrolytic technologies are analyzed in TE-2 [56]. Solar- and wind-sourced energy production and supply are analyzed in detail in TE-3 [57]. The development of carbon capture and storage technologies is introduced and examined in TE-4 [58]. The TE analysis of desalination technologies is provided in TE-6 [59], with consideration of an energy-water nexus [60].

3.2. Critical Reviews

3.2.1. Review of Recycling PV Panels

Without appropriate recycling and disposal, the rapidly increasing number of abandoned solar PV panels is likely to cause serious environmental problems, including hazardous waste, resource depletion, and GHG emissions. The risk from discarding panels irresponsibly has been shown in various studies. Bang et al. [61] conducted metal leachability tests on typical solar PV panels. These tests indicated emissions of Pb and Cd/Se and the potential for toxicity owing to materials such as Cu, Pb, Ni, and Ag from polycrystalline Si and CIGS (copper indium-gallium di-selenide) PV panels, as well as the potential for non-negligible resource depletion from polycrystalline Si PV panels (primarily caused by Ag). However, the current mainstream approach in many countries remains directed towards processing spent solar PV panels based on incineration and landfilling [62], and most optional recycling technologies are still in the experimental phase.

In addition to simple incineration and landfilling, several technology combinations have been proposed for fragmentation and recycling. During the pretreatment phase, for example, removing the junction box and Al frame can be easily facilitated by human force or automatic electrical machinery (**Fig. 2**).

In contrast to the process for removing the Al frame and junction box, removing the glass from Si cells is more complex owing to the polymeric encapsulation layers, mostly comprising ethylene vinyl acetate (EVA). Early practices usually directly crushed the panels into multi-sized particles, and then roasted the particles to remove the EVA. Recently, panels have been pretreated using a hot environment or hot knife to melt the EVA layer, such that the glass can be recovered as a complete piece from the cells. The following describes the current recycling technologies in detail.

i. Mechanical Delamination

The glass and valuable metals in cells can be directly crushed and sieved out from particles separately, owing to their density differences. Usually, the first process, shredding or hammer milling, will be repeated approximately three times. This is to reduce the fraction for thermal treatment, and to satisfy the requirements for a leaching treatment for recovering metals. EVA-glued layers are usually concentrated in a large fraction, directly recoverable glass is concentrated at an intermediate fraction of 0.4–1 mm, and metals and other recoverable glass are concentrated at fine fractions [63, 64]. Cooling the EVA layer at a sufficiently low temperature (-196°C) or creating oxidant hydrothermal subcritical conditions can also remove the EVA layer and detach all the glass from the cells, but the feasibility for scaling up and energy performance are insufficient [65]. As EVA can be burned at approximately 450°C without breaking the glass layer, using a hot knife method, e.g., a heated cutting blade or a fast-spinning steel brush, is a relatively time- and energy-saving method by which the glass layer can be easily detached from the interface with the cells [66]. In addition to the gravity separation of the particles after shredding and sieving, electrostatic separation has also been indicated as feasible for recycling metals from electronic waste, and has proven to be effective and environmentally friendly. It separates Ag and Si from polyethylene terephthalate at an efficiency higher than 95% [67]. However, the overall recycling efficiency of metals by mechanical treatments alone is quite limited by the particle size, as it has a very low potential for attracting better purchase prices for metals.

Recently, several new options have been reported. Zhang [68] completely decomposed plastics at 773 K for 30 min under a 0.5 L/min N_2 flow rate, and then recovered metals like Ga in a vacuum at 1123 K and a 1 Pa system pressure. Nevala [69] examined an electro-hydraulic fragmentation method, which produces a shockwave impulse to the metals on the Si wafer. The study determined that approximately 99% of the Cu, 60% of the Ag, and 80% of the Pb, Sn, and Al by weight could be recovered as high-purity particles (corresponding to different size ranges). Thus, this method presents a significant advantage over a conventional crushing method. Following mechanical treatment, the Si and metals are usually recovered by using hydrometallurgical methods, i.e., to obtain high-purity metals.

ii. Thermal Delamination

When recycling spent PV panels, the main target of thermal treatment is to remove the EVA layer between the glass and cells. Unlike mechanical treatments, a thermal treatment does not use force or a hot knife, but rather decomposes the EVA layer pyrolytically in an O_2 environment at approximately 500°C using combustible oils and gases. This method can be scaled up using existing equipment such as a tube furnace, fluidized bed reactor, and muffle furnace, but its holding time of approximately 30 min and high energy use present weaknesses relative to mechanical methods [68, 70]. Additionally, the thinner wafers have a higher probability of breakage in the thermal process, increasing the risk of subsequent wafer reuse [71].

iii. Chemical Delamination

The EVA layer can also be removed by chemical dissolution with inorganic or organic solvents, for example, immersion in nitric acid for 24 h, or dissolving in trichlorethylene at 80°C for 10 d [72, 73]. In a similar but faster method, Kim and Lee [74] shortened the process time to within 30 min by using o-dichlorobenzene as an organic solvent; they also used ultrasonic irradiation to enhance the reaction and shorten the process time to within 60 min (using toluene as a solvent). Chemical methods constitute a feasible way to completely recover the glass layer at any thickness, but are time-consuming and energy-intensive, and rapid batch processing is difficult.

iv. Hydrometallurgical Delamination

After delamination, the valuable metals and Si must be recovered by a hydrometallurgical treatment for recycling by metal industries. In a typical case, metals can be removed from Si cells through a mixture of nitric acid, hydrogen fluoride, and acetic acid, so that 80% of the Si can be recovered for reuse in new cells [75]. Similarly, Shin [76] used nitric acid and potassium hydroxide to dissolve Ag and Al, respectively, followed by using an etching paste containing phosphoric acid to remove the anti-reflection coating and emitter on the surface of the Si wafer. The recycled wafers were almost identical to new commercially available wafers in terms of efficiency. Another option was introduced by Huang [71] who confirmed the availability of electrowinning to recover Ag, Cu, Sn, and Pb after acid leaching based on Mecucci [77]. The results from sheet resistance monitoring revealed that the recovered metals and Si were sufficiently purified to be considered as fresh materials that could be sold profitably.

v. Technology Assessment

Although various methods appear feasible and effective in small-scale experiments, very few of them actually move on to commercialization; this is because of the high cost of machinery and reagents, as well as the low market price of the recovered glass and Si wafer [65, 78, 79]. Based on current technology developments and commercialization, many research groups have already started pre-evaluations of the environmental impacts of recycling systems based on LCAs. Although the details of their findings are different, the first consensus is that landfills and incineration are the worst solutions for disposing of abandoned solar PV panels, owing to their non-negligible environmental impact. Lunardi [62] applied the "ReCiPe" method to compare various disposal methods for abandoned solar PV panels. The results showed that landfill and incineration have 2–3 times more negative impacts on the ecosystem and human health than recycling technologies; notably, the impacts are similar between the mechanical, chemical, and thermal recycling methods. In a "cradle-to-grave" situation, recycling the abandoned solar PV panels may reduce $3/4$ of the terrestrial ecotoxicity, $1/4$ of the human toxicity potential, $1/4$ of the global warming potential, and $2/5$ of the acidification. Returning the recycled wafer to new production can reduce energy consumption by 70% in the case of thermal treatment [65, 75]. Without appropriate recycling systems and EoL management, abandoned solar PV panels (particularly those made of toxic materials such as CdTe panels)

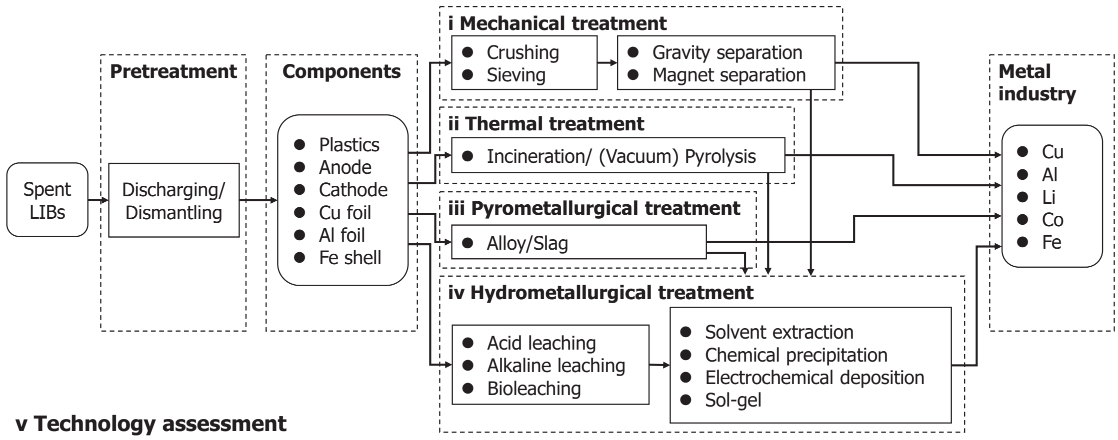

Fig. 3. Possible technology combinations for recycling spent LiBs with the contents of Subsection 3.2.2.

will cause significant environmental impacts, even though they perform better in energy and resource consumption by capacity [75, 80, 81].

3.2.2. Review of Recycling LiBs

Although LiBs have been broadly used in electric vehicles and electronic devices, the current system for disposing of spent batteries still relies on landfills without effective recycling of hazardous metals, thereby posing considerable risks to the environment and human health. Owing to recent technological developments, technologies for recycling both the anodes and cathodes of LiBs have become more economically feasible. However, most of the literature suggests that these technologies should not be applied individually, but should be combined, i.e., to completely recycle the secondary battery at a reasonable cost. Usually, the recycling of batteries attracts considerable attention, because they contain high-value metals such as Co and Ni. This section aims to summarize recycling technologies in a critical review, and refers to the latest critical reviews and reports on technology innovations [62, 82–89]. Based on this literature, a summary of the recycling technologies for spent LiBs is shown in **Fig. 3**.

As the first unavoidable process, pretreatment is introduced in most models, and aims to discharge and disassemble the spent LiBs. By human force or the use of machines, the spent LiBs are decomposed into the anode, cathode, organics, and other elements. Similar to the case with abandoned solar PV panels, there are several methods comprising specific processes for recovering valuable materials from cathodes.

i. Mechanical Treatment

The first choice, mechanical treatment, directly uses multistage crushing and sieving to separate metals, organics, and inorganics, according to their physical properties. The process usually involves using sieving and magnetic separation to separate metallic materials. For example, spent batteries can be shredded with a hammer mill to separate steels and plastics; then, the Al, Co, and Cu can be selected by screening with a shaking table. After the metallic oxides and graphite are separated from the cathode-rich undersized particles using a filter press, Na_2CO_3 and CO_2 are added to the mixing tank to produce Li_2CO_3, which is used in the metal industry [82]. With the current rapid developments in automation, LiBs can now be easily dismantled to remove the cathode, without requiring coarse crushing. Various processes are available for recycling the cathode, including mechanical methods, hydrometallurgy, pyrometallurgy, and biotreatment; even bacteria and fungi can be used as media.

ii. Thermal Treatment

As the industrial sector is paying more attention to recovering valuable metals (rather than the other parts), thermal treatment also represents a frequent approach, and is used to remove organic binders and graphite before hydrometallurgical treatment. After crushing or disassembling, the spent LiBs can be exposed to a furnace environment with air flow or $KHSO_4$ [90]. It has been reported that applying a relatively low incineration temperature ($<700°C$) for a long time may increase the leaching efficiency of metals into the leaching reagent [91]. A direct incineration treatment is thought to be effective and time-saving, but requires additional equipment for gas and smoke cleaning. Accordingly, other improvements (such as the pyrolysis method) have been discussed, aiming to enhance the eco-friendliness of thermal treatment [92].

iii. Pyrometallurgy Treatment

The thermal treatment introduced above is usually followed by hydrometallurgical treatment for metal recovery. In contrast, pyrometallurgical methods are more straightforward for recovering metals; they take advantage of the alloying character to separate metals into slags and alloys. For example, a highly purified alloy of Fe–Co–Ni–Cu ($>$ 99%) can be obtained by preparing a $MnO–SiO_2–Al_2O_3$, CaO, SiO_2, pyrolusite, and Al shells for spent LiBs at temperatures of 1475°C for 30 min [93]. The reservations relating to this method mainly concern its high energy consumption, equipment costs, gas emissions, strict requirements for environment control, and difficulty in recovering Li from the slag phase.

iv. Hydrometallurgy Treatment

The hydrometallurgy method usually includes leaching and extraction processes. Many applicable leaching methods have been introduced, including conventional inorganic acid leaching, organic acid leaching, alkaline leaching, bioleaching, intensified leaching, and selective leaching. Overall, acid leaching is the most widely applied process, and is thought to be reliable and ecofriendly for extracting highly purified valuable metals. Lixiviants are currently available as inorganic and organic acids, and there are differences between them in regard to economic and environmental performance. The former include sulfuric, hydrochloric, nitric, phosphoric, hydrofluoric, and other acids, i.e., relatively low-cost, energy-saving materials that are easy to use for the recovery of metals. The organic types include citric and oxalic acids, which can avoid gas emissions without significant corrosion of the equipment. In detail, using HCl can increase the leaching efficiency of Co without reductants over using HNO_3 and H_2SO_4, but the gas emitted from the process needs to be managed, and a complex separation and purification step is required. Most of the organic acids (for example, citric acid) reveal a higher leaching efficiency of Co than HCl and H_2SO_4, whereas the Li leaching efficiency is somewhat similar. However, some organic acids (such as oxalic acid) can play a double role as both reductant and leachant; the leaching efficiency of Co and Li can reach 97% and 98%, respectively [62, 94]. A summary of the acid leaching methods is provided in Appendix B.

In addition to the acid leaching method, alkaline leaching creates an alkaline environment, so as to allow hydroxide ions to interact with metals for leaching. For example, Al is very likely to be soluble in a NaOH solution at room temperature, whereas other elements such as Co, Ni, and Mn remain in the solid state [95, 96]. Additionally, ammonia leaching agents based on ammonia, ammonium carbonate, and ammonium sulfite are feasible methods for reducing the insoluble high-oxidation states of Ni and Co, and form more leachable ions such as $Cu(NH_3)_n^{2+}$, $Ni(NH_3)_n^{2+}$, and $Co(NH_3)_n^{2+}$ [97, 98].

Biometallurgical leaching is another method that is thought to have low economic cost and environmental impact, but is currently difficult to commercialize as an industrial process. For example, chemolithotrophic and acidophilic bacteria such as *Acidithiobacillus ferrooxidans* are reported to be feasible for nearly fully leaching out Co and Li, but the process might take a few days [99, 100]. Similar results have been reported for a mixed culture of sulfur-oxidizing and iron-oxidizing bacteria; they can also leach out Co and Li from spent LiBs over a long time [101]. In contrast, fungal bioleaching has a faster leaching process with a strong adaptation to a toxic environment, and thus has a high potential for industrialization. A typical case of using *Aspergillus niger* was reported by Horeh [102]. It can secrete mixed organic acids, such as malic, gluonic, oxalic, and citric acid, to leach out 100% of the Cu, 95% of the Li, 70% of the Mn, 65% of the Al, 45% of the Co, and 38% of the Ni in 2 weeks.

To increase the leaching efficiency and speed, supporting treatments including milling and ultrasonic waves have been indicated as effective. The former aims to enlarge the surface area for interaction [103] and the latter releases a large amount of energy on the interface between the solid and liquid by the cavitation effect [104].

After hydrometallurgical solution, the valuable metals can be separated and recovered by several methods, such as solvent extraction, chemical precipitation, electrochemical deposition, and sol-gels. Because the compounds after the leaching process are usually different in regard to relative solubility, the so-called solvent extraction introduces two immiscible liquids to separately recover different metals. Many extractants have been mentioned in previous studies, e.g., using di (2-ethylhexyl) phosphoric acid (D2EHPA) to extract Mn, Cu, and even Co [105, 106], and using bis (2,4,4-trimethylpentyl) phosphinic acid (Cyanex 272) to extract Co [107, 108]. The second method, chemical precipitation, uses the different precipitate performances of combinations of specific anions and metal cations to separate and recover metals after leaching; however, the extraction processes are usually complex, owing to the mixture of metals in the leaching solution. Coprecipitation and coupling with solvent extraction are two ideas for shortening the route and increasing the recycling efficiency when recovering metals. For example, the concentrations of Ni, Mn, and Co in a leaching solution can be coprecipitated with NaOH, Na_2CO_3, or $H_2C_2O_4$, respectively; then, Li_2CO_3 can be used to capture the cathode material $Ni_xCo_yMn_{1\text{-}x\text{-}y}O_2$ [109, 110]. Electrochemical deposition and sol-gel methods are also well-studied methods for the recovery of valuable metals, especially Co. For example, it has been reported that $LiCoO_2$ can be electrodeposited on a Ni substrate when leached by nitric acid with the electrolyte LiOH [111]. In contrast, as a well-referred case of the latter, the cathode active material $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ can be directly regenerated if a D, L-malic acid is used as both a leaching and a chelating agent through a sol-gel process [112].

v. Technology Assessment

Global practice has confirmed that an optimized combination of recycling technologies is effective and environmentally friendly when recycling spent LiBs (as opposed to applying technologies individually). To summarize, mechanical treatments are effective for rapid batch processing and energy saving, but the strict requirements relating to purity and particle size limit the sale price to metal industries. In contrast, thermal and pyrometallurgical treatments can easily remove graphite and plastics during incineration, but consume considerable energy and incur high costs for gas cleaning. Hydrometallurgical treatments can meet the purity requirements for metal recovery, but require additional pretreatments and mechanical treatments. Because selections of recycling technologies are related to the production processes of LiBs, many re-

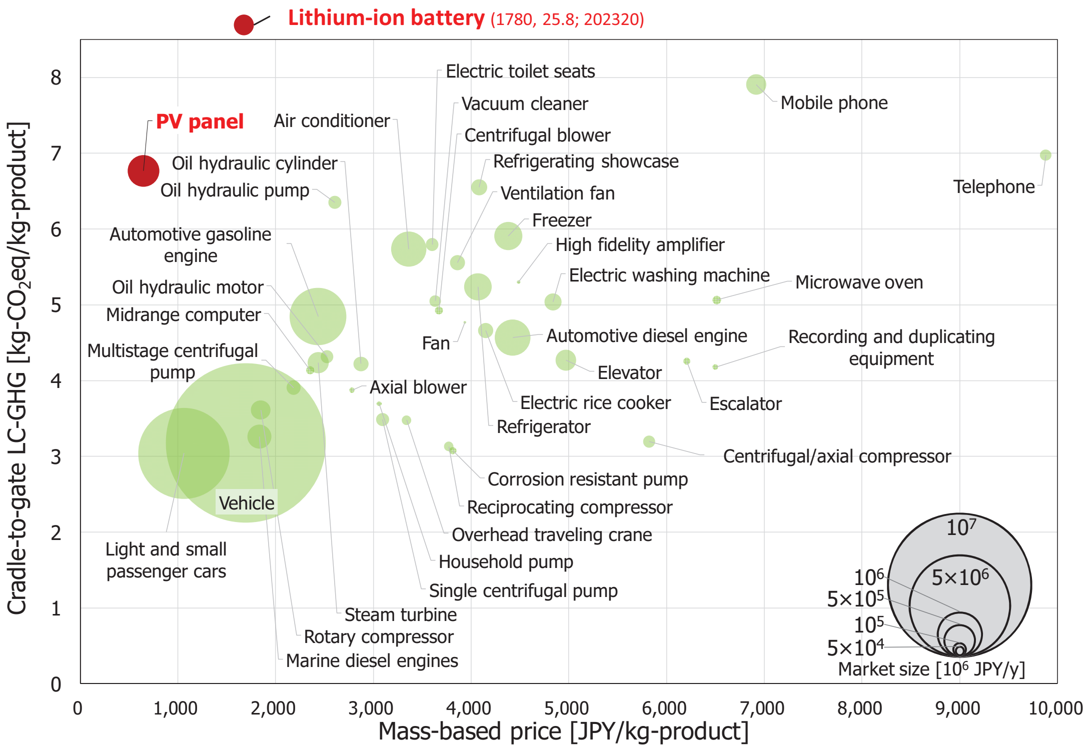

Fig. 4. Cradle-to-gate LC-GHG for mass-based price. Bubble size shows their market sizes [10^6 JPY/y].

searchers have considered LCAs of battery products. For example, battery cell production is found to contribute the most to LC-GHGs, whereas economic input-output systems contribute most of the life cycle energy consumption [113, 114]. Additionally, as the recycling process is based on the type of battery, the contribution of LC-GHGs and energy consumption is less than 10% for a $LiMn_2O_4$ battery, but in the case of a $Li(Ni_xCo_yMn_z)O_2$ battery, the contribution is more than 20% [115]. Currently, owing to a lack of accurate data, there is no consensus on the environmental impact of the life cycles of LiBs, but improved designs of the battery structure for easier dismantling and increased usage of ecofriendly compounds as cathode materials will certainly reduce the energy consumption, resource depletion, and environmental impact.

3.3. Intensities of Environmental Impacts for Unit Amount Production

The results of an intensity analysis for cradle-to-gate LC-GHGs are shown in **Fig. 4**. Relative to other products retrieved from IDEA v2.3, the PV panels and LiBs have relatively higher LC-GHG emissions per weight, but their mass-based prices are not higher than most of the other products contained in the LCI database. As higher prices mean larger inputs for manufacturing in general, there may be a positive correlation between prices and environmental impacts. In this context, PV panels and LiBs have higher slope factors than most of the other products. Similar results were obtained for resource use and the LIME index, as shown in **Figs. 5** and **6**, respectively. Thus, PV panels and LiBs have relatively greater environmental impacts per unit weight than other products in the LCI database.

The environmental impacts of vehicles per unit weight are smaller than those of LiBs. The vehicles referred to here are mainly internal combustion engine vehicles, and not battery-equipped vehicles. Thus, **Figs. 4–6** present the increases in environmental impacts from vehicle manufacturing when equipping them with LiBs; in contrast, the price is not largely changed by LiBs, at least directly.

For vehicle recycling systems, the recycling of LiBs has become an issue of reducing environmental impacts. A higher value in resource use means that the elements included in the LiBs, especially metals, should be recovered; otherwise, the life cycle resource use could become life cycle resource consumption. Recycling can reduce the consumption of the valuable and essential metals in LiBs, even if the resource use from LiB manufacturing is high. PV panels also have a higher LC resource use, as shown in **Fig. 5**. The spent PV panels should be treated appropriately to avoid resource consumption at the EoL of PV panels.

3.4. Requirement Definition of Technology Assessment for PV and LiB Recycling Systems

3.4.1. Towards Social Implementation

To design a *benign* recycling system, the requirements for a technology assessment should address the issues associated with recycling systems. Through the abovementioned analyses, the current status of the requirements for technology assessments of PV and LiB recycling systems were reviewed. The bibliometric analysis extracted the

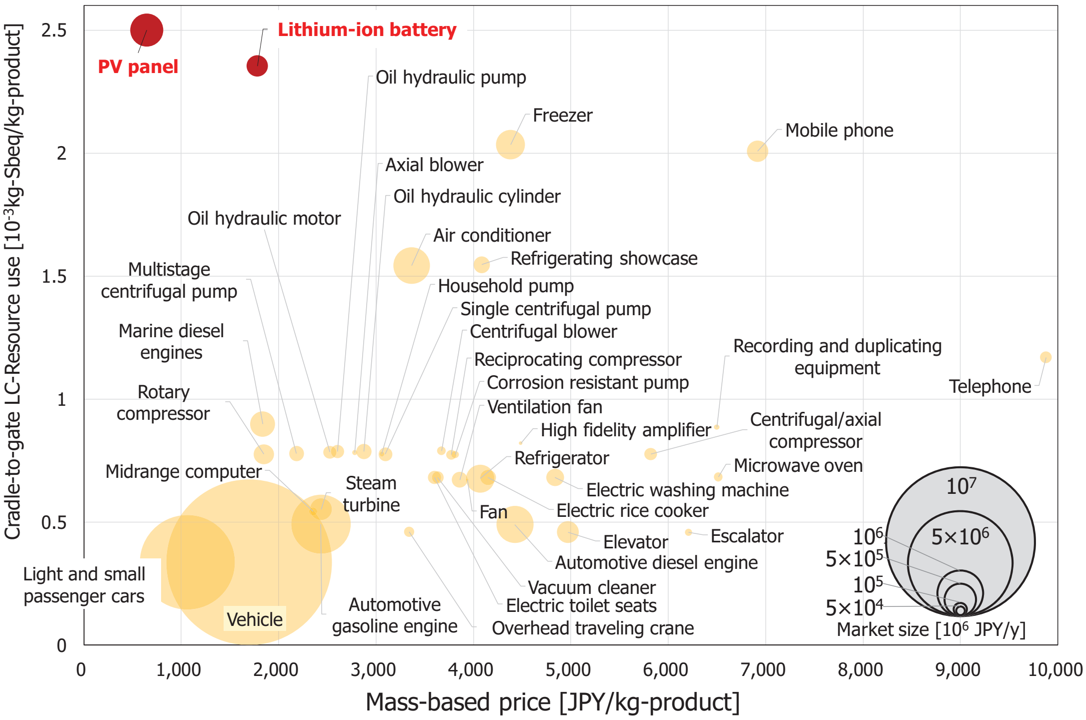

Fig. 5. Cradle-to-gate LC-resource use for mass-based price. Bubble size shows their market sizes [10^6 JPY/y].

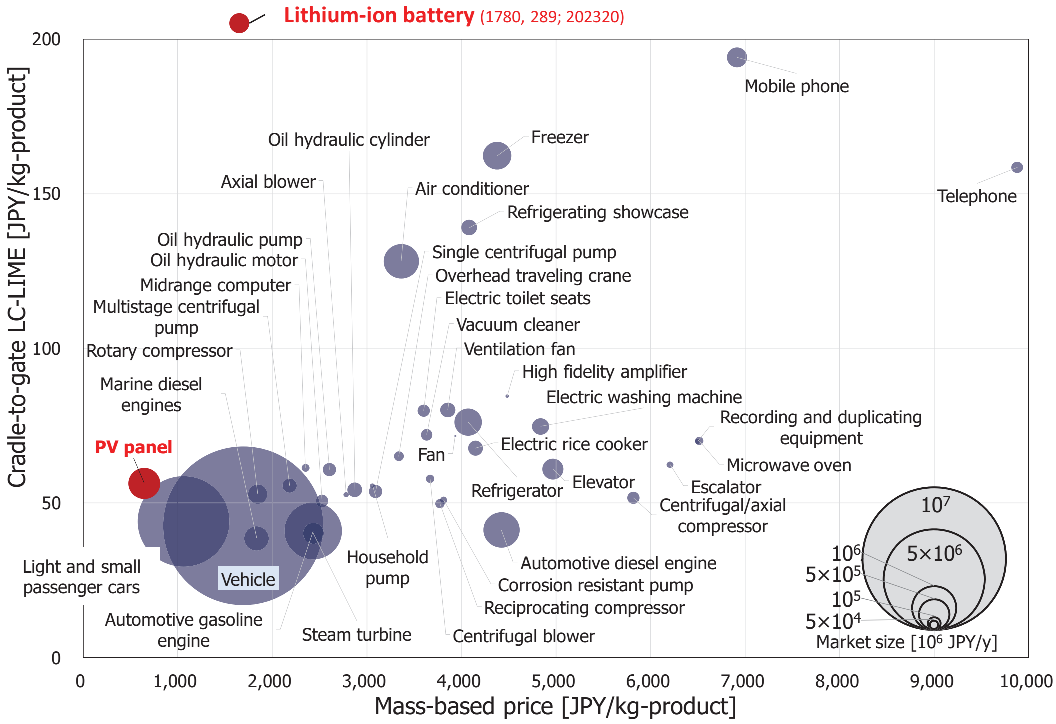

Fig. 6. Cradle-to-gate LC-LIME index for mass-based price. Bubble size shows their market sizes [10^6 JPY/y].

need to characterize the SE, ST, and TE aspects from previous (and other current) social issues. These aspects can be related to the social implementation of the possible technology options organized in Section 3.2. The circulation of the social and economic values should be determined for PV and LiB recycling, as studied in regard to the issues of ecosystem preservation, climate change, and solid waste (Appendix A1), and could be shown as the recovery of metal resources and the treatment of hazardous chemicals. Regarding the ST aspects, regime transitions such as those concerning infrastructure, laws, regulations, and social acceptance concerning the reuse of materials from spent PV panels and LiBs should be addressed (Appendix A2). Some of the industrial processes have already become accessible, for example, the pyrometallurgical and hydrometallurgical processes. Regime transitions are also related to the TE aspects of recycling technologies. In addition to the efficiency of the unit technology, for example, the recovery ratio of certain metals from PV panels or LiBs by a segregation technology and the collection and transport of spent products can change the total costs for recycling, owing to changes in the collectible amounts and contamination. The benefits induced by the recycling technologies for PV panels and LiBs fluctuate with the quality of the recovered materials. For the social implementation of recycling technologies for PV panels and LiBs, the social regime transitions and technology developments should be connected to each other, based on the circulation of the social and economic values derived by the recycling systems.

3.4.2. For Proof of Concept

Technology assessments are strongly needed for the proof of concept in recycling systems for PV panels and LiBs. The intensities of the environmental impacts examined in Section 3.3 clarified the relatively large cradle-to-gate life cycle impacts in the production of PV panels and LiBs. The options in recycling technologies and systems for PV panels and LiBs have wide possibilities in their combinations for recovering metals, according to the critical review in Section 3.2. There is a need to demonstrate how the environmental impacts could be avoided by recycling PV panels and LiBs. The proof of concept for implementing recycling into the EoL of products must be confirmed and addressed, as discussed in regard to Ta recycling from capacitors [116]. To realize planned recycling, the traceability of products at their EoL should be enhanced with an aim towards a sustainable global circulation of resources [117], and advances in automation and remote recycling control should be enabled [118]. Stakeholders should be networked and engaged for the circulation of resources [26]. Such information should be accessible during product design phases to determine the EoL options for products at the early stages of their life cycles [119], and to consider the options in product design for recycling (such as the modularity of parts) [120]. For example, a better design of solar PV panels, such as a simple structure for dismantling and identifying the encapsulation layer for easy delamination, can significantly shorten the recycling process and reduce the economic cost, energy consumption, and environmental impact.

The required data, settings, and conditions to be considered in the technology assessments are listed in **Table 1**. The LCA has become a strong tool for quantifying the environmental impacts through the life cycles of PV panels and LiBs, and is applicable for the proof of concept. The LC-GHG is, of course, an important indicator for global sustainability, but it is insufficient for resource circulation. The ecologically hazardous chemicals contained in PV panels and LiBs must be appropriately treated through EoL management. To avoid the flow of waste effluents into the environment, the metal resources must be carefully traced and assessed, whether they are used or consumed. If the metals are consumed by dilution into the environment, the metal resources may not be sustainably utilized in the future. The values of the cradle-to-gate LC resource use per unit amount of the PV panels and LiBs are relatively higher than those of the other assessed products, owing to the presence of metals; these metals could become ecotoxic chemicals if they are released/eluted to the environment (**Fig. 5**). Such inevitable resources for products must be recovered by implementing recycling technologies, the net value of which can be quantified using an LCA.

The cumulative environmental impacts from grid power often have a relatively higher contribution to the final LCA results, as most of the processes require electricity. LC-GHGs originate to a large extent from power generation from fossil fuel consumption in energy sectors. In this regard, the design of recycling systems should be based on their concepts, which are not always focused on reductions in GHG emissions, but rather on resource circulation. Because the GHG emissions originating from fossil fuels could be reduced by implementing renewable power sources, an LCA in a technology assessment of recycling systems for PV panels and LiBs should pay more attention to impact categories other than climate change if the recycling systems do not require much energy consumption. Thermal treatment and pyrometallurgy processes sometimes require massive energy, e.g., to operate high-temperature units. Chemical treatments may require additional energy to recover the used agents and provide waste chemical treatments. Waste treatments may consume water and emit wastewater, which can cause another environmental issue. Sophisticated LCAs should be conducted for the recycling technology options while considering the entire scopes of required processes, regional differences, and future possibilities.

The LCA should reveal the effective combination of technologies for the reuse/recycling of PV panels. As for the impact category, climate change and abiotic resource depletion should be specifically analyzed. Regarding the foreground data required for the LCA, there is a need for process inventory data regarding the reuse and recycling technologies. This must be acquired via experiments carried out in universities and actual plants in industry, as some of the technology options are now under development.

In addition to the LCA, a material flow analysis (MFA) should be simultaneously conducted for recycling systems, although few papers containing MFAs of PV panels and LiBs have been reported. MFAs can contribute to specifying possible flow rates within product life cycles, and should be carefully examined in the design of the scale of the technology option to be implemented. In particular, for recycling systems (not supply chains), the input to processes is waste, and its generation is uncontrollable. Waste generation values for designing the scales of recycling processes should be estimated [121] after

Table 1. Required data, settings, and conditions to be considered in technology assessments.

	PV panels	LiBs
Technology options	・Processes required for reuse of spent PV ・Performance and possible capacities of applicable technologies (e.g., those shown in Fig. 2) ・Technology combination for delamination with resource recovery technologies considering the demands of recycled metals and glasses	・Processes required for reuse of spent LiB ・Performance and possible capacities of applicable technologies (e.g., those shown in Fig. 3) ・Technology combination for dismantling with resource recovery technologies
LCA	・Cumulative life cycle inventories for different types of PV panels ・Lifetime including reusable periods, expected power generation, and necessity of maintenance ・Avoided centralized grid power (optional for the comparative assessment with other energy technologies) ・Process inventories of applicable reuse/recycling technologies ・Appropriate impact categories to assess technology options	・Cumulative life cycle inventories for different types and usage of LiBs ・Lifetime including reusable periods, expected changes in battery state of health (SOH), and necessity of maintenance ・Functions in usage of battery (optional for comparative assessment with other energy technologies) ・Process inventories of applicable reuse/recycling technologies ・Appropriate impact categories to assess technology options
MFA	・Annual shipment of PV panels considering their market penetration and saturation factors such as power grid constraints ・Failure curves of PV panels considering time-related deterioration and corruption by natural disasters ・Changes in efficiency and product trends resulting from new technological niche and regime transitions	・Annual shipment of products containing LiBs considering their market penetration and changes in possession rate ・Failure curves of LiBs and products containing LiBs ・Changes in efficiency and product trends resulting from new technological niches and regime transitions
Other viewpoints	・Update rates of PV panels after the periods of feed-in tariff for the power generated from PV panels ・Distribution of profit and cost burdens considering the contribution to the mitigation of fossil fuel consumption ・Circulation of metal resources and cash (including the manufacturers) ・Enactment of recycling law and regulations for PV panels	・Update rates of LiBs based on the reduction in the battery SOH ・Distribution of profit and cost burdens considering the circulation of the main products containing LiBs ・Circulation of metal resources and cash (including the manufacturers) ・Harmonization of LiB recycling systems with existing law and regulations for, e.g., car recycling.

the LCA, so as to confirm the unit amount of throughput [122]. Well-designed scales of recycling processes can contribute to good TE performance, as the operation ratio can be sufficiently increased. The demands for recycled products and materials should be matched with the industry through quality checks. If existing pyro- and hydrometallurgical processes are engaged in the recycling of PV panels and LiBs, their products can be used by the same user, as freshly produced materials. The contamination of multiple materials has become the reason why recycled products intended to replace freshly produced products often have low quality. Physical segregation can avoid contamination of the components in PV panels and LiBs, for example, glass, resins, Al, organic chemicals, and various metals.

An LCA and MFA of PV panels and LiBs should be conducted for the design of practical scenarios towards sustainable resource circulation, along with other related assessments. To implement the recycling systems in practice, the stakeholders should collaborate mutually. Based on the expected cost-benefit relationship, the profit and cost burdens should be distributed to stakeholders while considering the social values of PV and LiB recycling, such as the contributions to the mitigation of fossil fuel consumption and resource circulation. Laws and regulations should be formulated to realize the active circulation of waste-containing resources.

4. Conclusion

Technology assessments are necessary for designing and implementing recycling systems for PV panels and LiBs. This study reviewed the current possibilities of applicable technologies and systems options for recycling PV panels and LiBs, based on existing assessment case studies. A bibliometric analysis specified the need of assessments for the social implementation of new recycling systems. The requirements for the assessment of the management of the EoL of spent PV panels and LiBs were organized, to identify the key issues to be considered in further studies on their recycling.

The cradle-to-gate LC-resources used per unit amount in PV panels and LiBs are relatively higher than those for general industrial products owing to the metals they contain. This indicates that their prioritization for recycling is relatively higher than other target products in recycling laws and regulations. Various recycling technologies have been proposed for PV panels and LiBs. Most are divided into physical segregation methods and chemical treatments. For PV panel recycling, the transparent tempered flat glass should be separated from the PV cells containing Si, Cu, Ag, and other metals encapsulated by resins. The parts comprising the LiB should be appropriately dismantled and segregated to concentrate valuable metals such as Cu, Co, Ag, and Li. After such physical segregation, an adequate chemical treatment should be used for the recovery of metals as resources. As a requirement of the technology assessment, the proof of concept for recycling the PV panels and LiBs should be addressed. An LCA can be used to analyze the net changes in environmental impacts. An MFA should be applied to design the scale of the recycling process. The design and assessment of PV panels and LiBs should be conducted based on the implementation of technology options, circulation of resources by feasible cash flows, and appropriate laws and regulations.

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References:
[1] Y. Kishita and Y. Umeda, "Development of Japan's photovoltaic deployment scenarios in 2030," Int. J. Automation Technol., Vol.11, No.4, pp. 583-591, 2017.
[2] M. Elrawemi, L. Blunt, H. Muhamedsalih, F. Gao, and L. Fleming, "Implementation of in process surface metrology for R2R flexible PV barrier films," Int. J. Automation Technol., Vol.9, No.3, pp. 312-321, 2015.
[3] F. C. Padoan, P. Altimari, and F. Pagnanelli, "Recycling of end of life photovoltaic panels: A chemical prospective on process development," Solar Energy, Vol.177, pp. 746-761, 2019.
[4] Ministry of Economy, Trade and Industry (METI), Feed-in Tariff scheme in Japan. https://www.meti.go.jp/english/policy/energy_environment/renewable/pdf/summary201207.pdf [Accessed March 31, 2020]
[5] A. Paiano, "Photovoltaic waste assessment in Italy," Renew. Sustain. Energy Rev., Vol.41, pp. 99-112, 2015.
[6] https://ec.europa.eu/jrc/sites/jrcsh/files/jrc114616_li-ion_batteries_two-pager_final.pdf [Accessed March 31, 2020]
[7] Swiss Centre for Life Cycle Inventories; ecoinvent version 3.1. http://www.ecoinvent.org/database/ [Accessed December 8, 2018].
[8] H. K. Salim, R. A. Stewart, O. Sahin, and M. Dudley, "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review," J. of Cleaner Production, Vol.211, pp. 537-554, 2019.
[9] F. W. Geels, "Co-evolutionary and multi-level dynamics in transitions: the transformation of aviation systems and the shift from propeller to turbojet (1930–1970)," Technovation, Vol.26, pp. 999-1016, 2006.
[10] Y. Kikuchi, M. Nakai, Y. Kanematsu, K. Oosawa, T. Okubo, Y. Oshita, and Y. Fukushima, "Application of technology assessments into co-learning for regional transformation: A case study of biomass energy systems in Tanegashima," Sustain. Sci., Vol.15, No.5, pp. 1473-1494, doi: 10.1007/s11625-020-00801-12020, 2020.
[11] W. H. Liew, M. H. Hassim, and D. K. S. Ng, "Review of evolution, technology and sustainability assessments of biofuel production," J. of Cleaner Production, Vol.71, pp. 11-29, 2014.
[12] D. D. Ilic, E. Dotzauer, L. Trygg, and G. Broman, "Integration of biofuel production into district heating – part I: an evaluation of biofuel production costs using four types of biofuel production plants as case studies," J. of Cleaner Production, Vol.69, pp. 176-187, 2014.
[13] X. Ji and X. Long, "A review of the ecological and socioeconomic effects of biofuel and energy policy recommendations," Renew Sust. Energ. Rev., Vol.61, pp. 41-52, 2016.
[14] D. Neves, C. A. Silva, and S. Connors, "Design and implementation of hybrid renewable energy systems on micro-communities: a review on case studies," Renew Sust. Energ. Rev., Vol.31, pp. 935-946, 2014.
[15] E. K. Stigka, J. A. Paravantis, and G. K. Mihalakakou, "Social acceptance of renewable energy sources: a review of contingent valuation applications," Renew Sust. Energ. Rev., Vol.32, pp. 100-106, 2014.
[16] F. W. Geels, B. K. Sovacool, and S. Sorrell, "Sociotechnical transitions for deep decarbonization," Science, Vol.357, pp. 1242-1244, 2017.
[17] Innovation Policy Research Center at The University of Tokyo, Kajikawa Laboratory at Tokyo Institute of Technology, Academic Landscape, 2013. http://academic-landscape.com/ [Accessed March 31, 2020]
[18] Y. Kajikawa, J. Ohno, Y. Takeda, K. Matsushima, and H. Komiyama, "Creating an academic landscape of sustainability science: an analysis of the citation network," Sustain. Sci., Vol.2, pp. 221-231, 2007.
[19] Y. Kajikawa, "Research core and framework of sustainability science," Sustain. Sci., Vol.3, pp. 215-239, 2008.
[20] Y. Kikuchi, "Activity and data models for process assessment considering sustainability," Kagaku Kogaku Ronbunshu, Vol.40 pp. 211-223, 2014.
[21] E. Kiriyama and Y. Kajikawa, "A multilayered analysis of energy security research and the energy supply process," Appl. Energ., Vol.132, pp. 415-423, 2014.
[22] Y. Kikuchi, Y. Kanematsu, R. Sato, and T. Nakagaki, "Distributed cogeneration of power and heat within an energy management strategy for mitigating fossil fuel consumption," J. Ind. Ecol., Vol.20, pp. 289-303, 2016.
[23] Y. Kikuchi, "Simulation-based approaches for design of smart energy system: a review applying bibliometric analysis," J. Chem. Eng. Jpn., Vol.50, pp. 385-396, 2017.
[24] Thomson Reuters (2017) Web of Science. http://wokinfo.com/ [Accessed March 31, 2020].
[25] N. Shibata, Y. Kajikawa, Y. Takeda, and K. Matsushima, "Comparative study on methods of detecting research fronts using different types of citation," J. Assoc. Inf. Sci. Technol., Vol.60, pp. 571-580, 2009.
[26] H. Komoto, S. Kondoh, and K. Masui, "Simulating the Formation of Urban Mines Considering the Rational Decisions of Distributed End-of-Life Stakeholders," Int. J. Automation Technol., Vol.8, No.5, pp. 653-663, 2014.
[27] National Institute of Advanced Industrial Science and Technology (AIST) and Sustainable Management Promotion Organization (SuMPO), Inventory Database for Environmental Assessment (IDEA) v.2.3, 2020. http://idea-lca.com/?lang=en [Accessed March 31, 2020]
[28] "LCA Society of Japan." https://lca-forum.org/english/lime/ [Accessed March 31, 2020]
[29] L. Ager-Wick Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, "Life cycle assessment of a lithium-ion battery vehicle pack," J. Ind. Ecol., Vol.18, No.1, pp. 113-124, 2013.
[30] G. Majeau-Bettez, T. R. Hawkins, and A. H. Strømman, "Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles," Environ. Sci. Technol., Vol.45, No.10, pp. 4548-4554, 2011.
[31] Ministry of Internal Affairs and Communications, 2015 Input-Output Tables for Japan. http://www.soumu.go.jp/toukei_toukatsu/data/io/ [Accessed March 31, 2020]
[32] Ministry of Economy, Trade and Industry, Yearbook of current production statistics machinery 2018. https://www.meti.go.jp/statistics/tyo/seidou/result/ichiran/08_seidou.html [Accessed March 31, 2020]
[33] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," Renew. Sust. Energ. Rev., Vol.13, pp. 2263-2278, 2009.
[34] J. Domac, L. K. Richards, and S. Risovic, "Socio-economic drivers in implementing bioenergy projects," Biomass Bioenergy, Vol.28, pp. 97-106, 2005.
[35] L. C. Dreyer, M. Z. Hauschild, and J. Schierbeck, "A framework for social life cycle impact assessment," Int. J. Life Cycle Assess, Vol.11, pp. 88-97, 2006.
[36] M. Kanagawa and T. Nakata, "Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries," Energy Policy, Vol.36, pp. 2016-2029, 2008.

[37] A. Smith, A. Stirling, and F. Berkhout, "The governance of sustainable socio-technical transitions," Res. Policy, Vol.34, pp. 1491-1510, 2005.

[38] A. Smith, "Translating sustainabilities between green niches and socio-technical regimes," Technol. Anal. Strateg., Vol.19 pp. 427-450, 2007.

[39] F. W. Geels and J. Schot, "Typology of sociotechnical transition pathways," Res. Policy, Vol.36, pp. 399-417, 2007.

[40] M. Berg, "Patient care information systems and health care work: a sociotechnical approach," Int. J. Med . Inform., Vol.55, pp. 87-101, 1999.

[41] S. Sawyer, J. P. Allen, and H. Lee, "Broadband and mobile opportunities: a socio-technical perspective," J. Inf. Technol., Vol.18, pp. 121-136, 2003.

[42] T. Reiman and P. Oedewald, "Assessment of complex sociotechnical systems – theoretical issues concerning the use of organizational culture and organizational core task concepts," Safety Science, Vol.45, pp. 745-768, 2007.

[43] S. Niederer and J. van Dijck, "Wisdom of the crowd or technicity of content? Wikipedia as a sociotechnical system," New Media Soc., Vol.12, pp. 1368-1387, 2010.

[44] M. Clement and M. J. Guitton, "Interacting with bots online: users' reactions to actions of automated programs in Wikipedia," Comput Hum Behav, Vol.50, pp. 66-75, 2015.

[45] I. F. Ballo, "Imagining energy futures: sociotechnical imaginaries of the future Smart Grid in Norway," Energy Res. Soc. Sci., Vol.9, pp. 9-20, 2015.

[46] B. K. Sovacool, J. Axsen, and W. Kempton, "The future promise of vehicle-to-grid (V2G) integration: A sociotechnical review and research agenda," Annu. Rev. Env. Resour, Vol.42, pp. 377-406, 2017.

[47] L. Levidow and T. Papaioannou, "Policy-driven, narrative-based evidence gathering: UK priorities for decarbonisation through biomass," Sci. Publ. Policy, Vol.43, pp. 46-61, 2016.

[48] H. T. Kulve and A. Rip, "Constructing productive engagement: pre-engagement tools for emerging technologies," Sci. Eng. Ethics, Vol.17, pp. 699-714, 2011.

[49] T. van der Schoor and B. Scholtens, "Power to the people: local community initiatives and the transition to sustainable energy," Renew. Sust. Energ. Rev., Vol.43, pp. 666-675, 2015.

[50] L. Vesnic-Alujevic, M. Breitegger, and A. G. Pereira, "What smart grids tell about innovation narratives in the European Union: hopes, imaginaries and policy," Energy Res. Soc. Sci., Vol.12, pp. 16-26, 2016.

[51] E. Gnansounou and A. Dauriat, "Techno-economic analysis of lignocellulosic ethanol: a review," Bioresource Technol., Vol.101, pp. 4980-4991, 2010.

[52] D. Klein-Marcuschamer, C. Turner, M. Allen, P. Gray, R. G. Dietzgen, P. M. Gresshoff, B. Hankamer, K. Heimann, P. T. Scott, E. Stephens, R. Speight, and L. K. Nielsen, "Technoeconomic analysis of renewable aviation fuel from microalgae, Pongamia pinnata, and sugarcane," Biofuel Bioprod Bior., Vol.7, pp. 416-428, 2013.

[53] B. Wang, B. H. Gebreslassie, and F. Q. You, "Sustainable design and synthesis of hydrocarbon biorefinery via gasification pathway: integrated life cycle assessment and technoeconomic analysis with multiobjective superstructure optimization," Comput. Chem. Eng., Vol.52, pp. 55-76, 2013.

[54] F. C. Luz, M. H. Rocha, E. E. S. Lora, O. J. Venturini, R. V. Andrade, M. M. V. Leme, and O. A. del Olmo, "Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil," Energ. Convers Manage, Vol.103, pp. 321-337, 2015.

[55] A. D. Hawkes, P. Aguiar, C. A. Hernandez-Aramburo, M. A. Leach, N. P. Brandon, T. C. Green, and C. S. Adjiman, "Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power," J. Power Sources, Vol.156, pp. 321-333, 2006.

[56] M. Patel, X. L. Zhang, and A. Kumar, "Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review," Renew. Sust. Energ. Rev., Vol.53, pp. 1486-1499, 2016.

[57] H. X. Yang, W. Zhou, and C. Z. Lou, "Optimal design and techno-economic analysis of a hybrid solar-wind power generation system," Appl. Energ., Vol.86, pp. 163-169, 2009.

[58] D. Singh, E. Croiset, P. L. Douglas, and M. A. Douglas, "Techno-economic study of CO_2 capture from an existing coal-fired power plant: MEA scrubbing vs. O_2/CO_2 recycle combustion," Energy Convers Manag., Vol.44, pp. 3073-3091, 2003.

[59] T. Mezher, H. Fath, Z. Abbas, and A. Khaled, "Techno-economic assessment and environmental impacts of desalination technologies," Desalination, Vol.266, pp. 263-273, 2011.

[60] M. W. Shahzad, M. Burhan, L. Ang, and K. C. Ng, "Energy-water-environment nexus underpinning future desalination sustainability," Desalination, Vol.413, pp. 52-64, 2017.

[61] Y. Y. Bang, N. J. Hong, D. S. Lee, and S. R. Lim, "Comparative assessment of solar photovoltaic panels based on metal-derived hazardous waste, resource depletion, and toxicity potentials," Int. J. Green Energ., Vol.15, No.10, pp. 550-557, 2018.

[62] M. M. Lunardi, J. P. Alvarez-Gaitan, J. I. Bilbao, and R. Corkish, "Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules," Appl. Sci., Vol.8, 1396, 2018.

[63] F. Pagnanelli, E. Moscardini, G. Granata, T. Abo Atia, P. Altimari, T. Havlik, and L. Toro, "Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies," Waste Management, Vol.59, pp. 422-431, 2017.

[64] G. Granata, F. Pagnanelli, E. Moscardini, T. Havlik, and L. Toro, "Recycling of photovoltaic panels by physical operations," Solar Energy Materials and Solar Cells, Vol.123, pp. 239-248, 2014.

[65] R. Deng, N. L. Chang, Z. Ouyang, and C. M. Chong, "A techno-economic review of silicon photovoltaic module recycling," Renew Sustain. Energ. Rev., Vol.109, pp. 532-550, 2019.

[66] K. Komoto, J. S. Lee, J. Zhang, D. Ravikumar, P. Sinha, A. Wade, and G. Heath, "End-of-life management of photovoltaic panels: trends in PV module recycling technologies," National Renewable Energy Lab. (NREL), Golden, CO (United States), 2018.

[67] Z. Zhang, B. Sun, J. Yang, Y. Wei, and S. He, "Electrostatic separation for recycling silver, silicon and polyethylene terephthalate from waste photovoltaic cells," Modern Physics Letters B, Vol.31, No.11, 1750087, 2017.

[68] L. G. Zhang and Z. M. Xu, "Separating and Recycling Plastic, Glass, and Gallium from Waste Solar Cell Modules by Nitrogen Pyrolysis and Vacuum Decomposition," Environ. Sci. Technol., Vol.50, No.17, pp. 9242-9250, 2016.

[69] S. M. Nevala, J. Hamuyuni, T. Junnila, T. Sirviö, S. Eisert, B. P. Wilson, R. Serna-Guerrero, and M. Lundström, "Electro-hydraulic fragmentation vs conventional crushing of photovoltaic panels – Impact on recycling," Waste Management, Vol.87, pp. 43-50, 2019.

[70] J. K. Lee, J. S. Lee, Y. S. Ahn, G. H. Kang, H. E. Song, M. G. Kang, Y. H. Kim, and C. H. Cho, "Simple pretreatment processes for successful reclamation and remanufacturing of crystalline silicon solar cells," Progress in Photovoltaics: Research and Applications, Vol.26, No.3, pp. 179-187, 2018.

[71] W. H. Huang, W. J. Shin, L. Wang, W. C. Sun, and M. Tao, "Strategy and technology to recycle wafer-silicon solar modules," Solar Energy, Vol.144, pp. 22-31, 2017.

[72] V. Fiandra, L. Sannino, C. Andreozzi, and G. Graditi, "End-of-life of silicon PV panels: A sustainable materials recovery process," Waste Management, Vol.84, pp. 91-101, 2019.

[73] T. Doi, I. Tsuda, H. Unagida, A. Murata, K. Sakuta, and K. Kurokawa, "Experimental study on PV module recycling with organic solvent method," Solar Energy Materials and Solar Cells, Vol.67, Nos.1-4, pp. 397-403, 2001.

[74] Y. Kim and J. Lee, "Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent," Solar energy materials and solar cells, Vol.98, pp. 317-322, 2012.

[75] M. Vellini, M. Gambini, and V. Prattella, "Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels," Energy, Vol.138, pp. 1099-1111, 2017.

[76] J. Shin, J. Park, and N. Park, "A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers," Solar Energy Materials and Solar Cells, Vol.162, pp. 1-6, 2017.

[77] A. Mecucci and K. Scott, "Leaching and electrochemical recovery of copper, lead and tin from scrap printed circuit boards," J. Chem. Technol. Biotechnol., Vol.77, No.4, pp. 449-457, 2002.

[78] H. K. Salim, R. A. Stewart, O. Sahin, and M. Dudley, "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review," J. of Cleaner Production, Vol.211, pp. 537-554, 2019.

[79] S. Mahmoudi, N. Huda, Z. Alavi, M. T. Islam, and M. Behnia, "End-of-life photovoltaic modules: A systematic quantitative literature review," Resour Conserv Recycling, Vol.146, pp. 1-16, 2019.

[80] Y. Xu, J. Li, Q. Tan, A. L. Peters, and C. Yang, "Global status of recycling waste solar panels: A review," Waste Management, Vol.75, pp. 450-458, 2018.

[81] D. Sica, O. Malandrino, S. Supino, M. Testa, and M. C. Lucchetti, "Management of end-of-life photovoltaic panels as a step towards a circular economy," Renew Sustain Energ. Rev., Vol.82, pp. 2934-2945, 2018.

[82] O. Velázquez-Martínez, J. Valio, A. Santasalo-Aarnio, M. Reuter, and R. Serna-Guerrero, "A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective," Batteries, Vol.5, No.4, 68, 2019.

[83] P. K. Choubey, K. S. Chung, M. Kim, J. Lee, and R. R. Srivastava, "Advance review on the exploitation of the prominent energy-storage element Lithium, Part II: From sea water and spent lithium ion batteries (LIBs)," Minerals Engineering, Vol.110, pp. 104-121, 2017.

[84] P. Meshram, A. Mishra, Abhilash, and R. Sahu, "Environmental impact of spent lithium ion batteries and green recycling perspectives by organic acids–A review," Chemosphere, Vol.242, 125291, 2020.

[85] Y. Yao, M. Zhu, Z. Zhao, B. Tong, Y. Fan, and Z. Hua, "Hydrometallurgical Processes for Recycling Spent Lithium-Ion Batteries: A Critical Review," ACS Sustain Chem. Eng., Vol.6, No.11, pp. 13611-13627, 2018.

[86] B. Swain, "Recovery and recycling of lithium: A review," Separation and Purification Technology, Vol.172, pp. 388-403, 2017.

[87] R. Golmohammadzadeh, F. Faraji, and F. Rashchi, "Recovery of lithium and cobalt from spent lithium ion batteries (LIBs) using organic acids as leaching reagents: A review," Resour. Conserv. Recycling, Vol.136, pp. 418-435, 2018.

[88] C. Liu, J. Lin, H. Cao, Y. Zhang, and Z. Sun, "Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review," J. of Cleaner Production, Vol.228, pp. 801-813, 2019.

[89] X. L. Zeng, J. H. Li, and N. Singh, "Recycling of Spent Lithium-Ion Battery: A Critical Review," Environ. Sci. Technol., Vol.44, No.10, pp. 1129-1165, 2014.

[90] J. F. Paulino, N. G. Busnardo, and J. C. Afonso, "Recovery of valuable elements from spent Li-batteries," J. hazard. Mat., Vol.150, No.3, pp. 843-849, 2008.

[91] C. Hanisch, T. Loellhoeffel, J. Diekmann, K. J. Markley, W. Haselrieder, and A. Kwade, "Recycling of lithium-ion batteries: a novel method to separate coating and foil of electrodes," J. of Cleaner Production, Vol.108, pp. 301-311, 2015.

[92] L. Sun and K. Qiu, "Organic oxalate as leachant and precipitant for the recovery of valuable metals from spent lithium-ion batteries," Waste Management, Vol.32, No.8, pp. 1575-1582, 2012.

[93] R. Guoxing et al., "Recovery of Valuable Metals from Spent Lithium-Ion Batteries by Smelting Reduction Process Based on $MnO-SiO_2-Al_2O_3$ Slag System," R. G. Reddy, P. Chaubal, P. C. Pistorius, and U. Pal (Eds.), "Advances in Molten Slags, Fluxes, and Salts: Proc. of the 10th International Conference on Molten Slags, Fluxes and Salts 2016," pp. 211-218, Springer, 2016.

[94] L. Li, L. Zhai, X. Zhang, J. Lu, R. Chen, F. Wu, and K. Amine, "Recovery of valuable metals from spent lithium-ion batteries by ultrasonic-assisted leaching process," J. Power Sources, Vol.262, pp. 380-385, 2014.

[95] D. A. Ferreira, L. M. Z. Prados, D. Majuste, and M. B. Mansur, "Hydrometallurgical separation of aluminium, cobalt, copper and lithium from spent Li-ion batteries," J. Power Sources, Vol.187, No.1, pp. 238-246, 2009.

[96] L. Chen, X. C. Tang, Y. Zhang, L. X. Li, Z. W. Zeng, and Y. Zhang, "Process for the recovery of cobalt oxalate from spent lithium-ion batteries," Hydrometallurgy, Vol.108, pp. 80-86, 2011.

[97] E. Rudnik, M. Pierzynka, and P. Handzlik, "Ammoniacal leaching and recovery of copper from alloyed low-grade e-waste," J. Material Cycles and Waste Management, Vol.18, pp. 318-328, 2016.

[98] A. Katsiapi, P. E. Tsakiridis, P. Oustadakis, and S. Agatzini-Leonardou, "Cobalt recovery from mixed Co-Mn hydroxide precipitates by ammonia-ammonium carbonate leaching," Minerals Engineering, Vol.23, No.8, pp. 643-651, 2010.

[99] D. Mishra, D. J. Kim, D. E. Ralph, J. G. Ahn, and Y. H. Rhee, "Bioleaching of metals from spent lithium ion secondary batteries using Acidithiobacillus ferrooxidans," Waste Management, Vol.28, No.2, pp. 333-338, 2008.

[100] G. Zeng, S. Luo, X. Deng, L. Li, and C. Au, "Influence of silver ions on bioleaching of cobalt from spent lithium batteries," Minerals Engineering, Vol.49, pp. 40-44, 2013.

[101] B. Xin, D. Zhang, X. Zhang, Y. Xia, F. Wu, S. Chen, and L. Li, "Bioleaching mechanism of Co and Li from spent lithium-ion battery by the mixed culture of acidophilic sulfur-oxidizing and iron-oxidizing bacteria," Bioresource Technology, Vol.100, No.24, pp. 6163-6169, 2009.

[102] N. B. Horeh, S. Mousavi, and S. Shojaosadati, "Bioleaching of valuable metals from spent lithium-ion mobile phone batteries using Aspergillus niger," J. Power Sources, Vol.320, pp. 257-266, 2016.

[103] J. Guan, Y. Li, Y. Guo, R. Su, G. Gao, H. Song, H. Yuan, B. Liang, and Z. Guo, "Mechanochemical process enhanced cobalt and lithium recycling from wasted lithium-ion batteries." ACS Sustain Chem Eng, Vol.5, No.1, pp. 1026-1032, 2017.

[104] L. Zhang, W. Guo, J. Peng, J. Li, G. Lin, and X. Yu, "Comparison of ultrasonic-assisted and regular leaching of germanium from by-product of zinc metallurgy," Ultrasonics sonochemistry, Vol.31, pp. 143-149, 2016.

[105] F. Wang, R. Sun, J. Xu, Z. Chen, and M. Kang, "Recovery of cobalt from spent lithium ion batteries using sulphuric acid leaching followed by solid-liquid separation and solvent extraction," RSC Advances, Vol.6, No.88, pp. 85303-85311, 2016.

[106] S. H. Joo, D. Shin, C. H. Oh, J. P. Wang, and S. M. Shin, "Extraction of manganese by alkyl monocarboxylic acid in a mixed extractant from a leaching solution of spent lithium-ion battery ternary cathodic material," J. Power Sources, Vol.305, pp. 175-181, 2016.

[107] J. Kang, G. Senanayake, J. Sohn, and S. M. Shin, "Recovery of cobalt sulfate from spent lithium ion batteries by reductive leaching and solvent extraction with Cyanex 272," Hydrometallurgy, Vol.100 Nos.3-4, pp. 168-171, 2010.

[108] A. K. Jha, M. K. Jha, A. Kumari, S. K. Sahu, V. Kumar, and B. D. Pandey, "Selective separation and recovery of cobalt from leach liquor of discarded Li-ion batteries using thiophosphinic extractant," Separation and Purification Technology, Vol.104, pp. 160-166, 2013.

[109] E. Gratz, Q. Sa, D. Apelian, and Y. Wang, "A closed loop process for recycling spent lithium ion batteries," J. Power Sources, Vol.262, pp. 255-262, 2014.

[110] L. Yang and G. Xi, "Preparation and Electrochemical Performance of LiNi 1/3 Co 1/3 Mn 1/3 O 2 Cathode Materials for Lithium-ion Batteries from Spent Mixed Alkaline Batteries," J. Electronic Materials, Vol.45, pp. 301-306, 2016.

[111] L. Li, R. Chen, F. Sun, F. Wu, and J. Liu, "Preparation of LiCoO2 films from spent lithium-ion batteries by a combined recycling process," Hydrometallurgy, Vol.108, Nos.3-4, pp. 220-225, 2011.

[112] L. Yao, H. Yao, G. Xi, and Y. Feng, "Recycling and synthesis of $LiNi_{1/3}$ $Co_{1/3}$ $Mn_{1/3}$ O_2 from waste lithium ion batteries using D,L-malic acid," RSC Advances, Vol.6, No.22, pp. 17947-17954, 2016.

[113] M. A. Pellow, H. Ambrose, D. Mulvaney, R. Betita, and S. Shaw, "Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues," Sustainable Materials and Technologies, Vol.23, e00120, 2020.

[114] M. A. Cusenza, S. Bobba, F. Ardente, M. Cellura, and F. D. Persio, "Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles," J. of Cleaner Production, Vol.215, pp. 634-649, 2019.

[115] S. P. Zhao and F. Q. You, "Comparative life-cycle assessment of Li-ion batteries through process-based and integrated hybrid approaches," ACS Sustain Chem. Eng., Vol.7, No.5, pp. 5082-5094, 2019.

[116] A. Heiho, Y. Kanematsu, M. Nagase, S. Murakami, C. Tokoro, and Y. Kikuchi, "Life cycle assessment of resource recovery from waste electrical and electronic equipment: A case study of Tantalum recovery by chain-using drum-typed impact mill," Kagaku Kogaku Ronbunshu, Vol.45, No.6, pp. 244-252, 2019.

[117] Y. Kishita, E. Kunii, S. Fukushige, Y. Umeda, and J. Fujimoto, "Scenario Analysis of Global Resource Circulation with Traceability Index Targeting Sustainable Manufacturing," Int. J. Automation Technol., Vol.3, No.1, pp. 3-10, 2009.

[118] M. Matsumoto, N. Mishima, and S. Kondoh, "Tele-Inverse Manufacturing – An International E-Waste Recycling Proposal," Int. J. Automation Technol., Vol.3, No.1, pp. 11-18, 2009.

[119] S. Okumura, Y. Matsumoto, Y. Hatanaka, and K. Ogohara, "Simultaneous Evaluation of Environmental Impact and Incurred Cost on Selection of End-Of-Life Products Recovery Options," Int. J. Automation Technol., Vol.10, No.5, pp. 699-707, 2016.

[120] S. Fukushige, Y. Inoue, K. Tonoike, and Y. Umeda, "Design Methodology for Modularity Based on Life Cycle Scenario," Int. J. Automation Technol., Vol.3, No.1, pp. 40-48, 2009.

[121] Y. Kikuchi, M. Hirao, H. Sugiyama, S. Papadokonstantakis, K. Hungerbühler, T. Ookubo, and A. Sasaki, "Design of recycling system for poly (methyl methacrylate) (PMMA), Part 2: Process hazards and material flow analysis," Int. J. Life Cycle Assess., Vol.19, No.2, pp. 307-319, 2014.

[122] Y. Kikuchi, M. Hirao, T. Ookubo, and A. Sasaki, "Design of Recycling System for Poly (Methyl Methacrylate) (PMMA) Part 1: Recycling Scenario Analysis," Int. J. Life Cycle Assess., Vol.19, No.1, pp. 120-129, 2014.

Appendix A. Results of Bibliometric Analysis

Each cluster was characterized by frequently used keywords, the number of articles, edge, and average times cited.

A.1. Obtained clusters for socioeconomic criterion. The SE-5 cluster is decomposed into subclusters from SE-5-1 to SE-5-10.

Cluster (No. of articles; edge; average times cited)	Keywords in descending order of term frequency; inverse class frequency
SE-1 Disease (20,173; 158,330, and 7.85)	Mortality, inequalities in health, cardiovascular, smoking
SE-2 Obesity (20145, 78442, and 3.89)	Overweight, childhood, adolescent, BMI, adolescent, asthma
SE-3 Child development (16548, 51422, and 3.11)	Dental, childhood, adolescent, school, cognitive
SE-4 Cancer (11549, 46951, and 4.07)	Patient, pylorus, screening, disparity, stage, mortality
SE-5 Ecosystem (8952, 15136, and 1.69)	Water, land, conservation, forest, fishery, climate, farmer, marine
SE-6 Multimorbidity (3971, 7430, and 1.87)	HIV, suicide, tuberculosis, infection, patient, mental, risk
SE-5-1 Agriculture and forestry (1028, 1900, and 1.85)	Farmer, forest, soil, crop, agroforestry, conservation, soil fertility
SE-5-2 Fishery (758, 2123, and 2.80)	Marine production, coral reef, fishing, marine protected area (MPA)
SE-5-3 Coastal zone (397, 549, and 1.38)	Water, ecosystem, coastal management, sea level
SE-5-4 Climate change (396, 536, and 1.35)	Adaptive management, water, climate, land, scenario, adaptation, natural resource management
SE-5-5 Energy (364, 545, and 1.50)	Renewable energy, biofuels, biomass, jatropha, sugarcane, input–output analysis, life cycle assessment
SE-5-6 Wetland (344, 540, and 1.57)	Mangrove, aquaculture, shrimp, forest
SE-5-7 Access to energy (332, 445, and 1.34)	Rural and urban, fuelwood, cooking, stove, household
SE-5-8 Solid waste (314, 681, and 2.17)	Management of solid waste, municipal waste
SE-5-9 Water (282, 346, and 1.23)	Water resource, river, climate change, irrigation
SE-5-10 Wildlife (246, 384, and 1.56)	Conservation area, forest, bushmeat, hunting

A.2. Obtained clusters for the sociotechnical criterion.

Cluster (No. of articles; edge; average times cited)	Keywords in descending order of term frequency; inverse class frequency
ST-1 Transition (620, 3564, and 5.75)	Innovation, niche, regime, sustainability transition, multilevel perspective, low carbon
ST-2 Health care (588, 1522, and 2.59)	Patient, ergonomics, nurse, clinical, medication
ST-3 Information system (233, 329, and 1.41)	Mobile, broadband, network, social medium
ST-4 Safety (228, 403, and 1.77)	Accident, resilience, awareness, incident, risk, cognition, organizational factors
ST-5 Energy (172, 273, and 1.59)	ST imaginary, renewable energy, smart grid, electric vehicle, solar, nanotechnology
ST-6 ST systems (79, 83, and 1.05)	Wikipedia, bot, Zephyr, help instance, online system

A.3. Obtained clusters for technoeconomic criterion.

Cluster (No. of articles; edge; average times cited)	Keywords in descending order of term frequency; inverse class frequency
TE-1 Liquid biofuel (611, 2354, and 3.85)	Ethanol, biodiesel, algae, biomass, pretreatment, fermentation, lignocellulose
TE-2 Pyrolysis (477, 1403, and 2.94)	Coal, biomass, gasification, IGCC, power plant
TE-3 Solar and wind (461, 1857, and 4.03)	Solar, wind, battery, hybrid system, grid, storage
TE-4 CCS (268, 489, and 1.82)	Carbon capture and storage (CCS), power plant, post combustion, membrane
TE-5 Biogas (90, 115, and 1.28)	Landfill, membrane, fuel cell, combined heating and power, hydrogen
TE-6 Desalination (77, 113, and 1.47)	Multistage flash distillation, multi-effect distillation, reverse osmosis, seawater

Appendix B. Typical Acid Leaching Methods and the Main Process

A summary of the acid leaching methods is shown below.

Typical method	Main process
Inorganic acid leaching No selectivity can be seen; Gas emission; Corrosion of equipment; Easier separation; Low free energy; Highly flammable; Lower cost than organic acid	
Hydrochloric acid	$2LiCoO_2 + 8HCl \rightarrow 2CoCl_2 + Cl_2 + 2LiCl + 4H_2O$
Sulfuric acid	$3H_2SO_4 + 2LiCoO_2 + 2H_2O_2 \rightarrow Li_2SO_4 + 5H_2O + 1.5O_2 + 2CoSO_4$
Organic acid leaching Selectivity is possible; No gas emission; No corrosion of equipment; Difficult separation; High free energy; nonflammable; higher cost than organic acid	
Citric acid	$18LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2 + 18H_3Cit + C_6H_{12}O_6 \rightarrow 6Li_3Cit + 2Ni_3(Cit)_2 + 2Co_3(Cit)_2 + 2Mn_3(Cit)_2 + 33H_2O + 6CO_2$
Oxalic acid	$4H_2C_2O_4 + 2LiCoO_2 \rightarrow CoC_2O_4 + LiHC_2O_4 + 2CO_2 + 4H_2O$
Tartaric acid	$2LiCoO_2$ (s) + $3C_4H_6O_6$ (aq) + H_2O_2 (aq) $C_4H_4O_6Li_2$ (aq) + $2C_4H_4O_6Co$ (aq) + $4H_2O$ (l) + O_2 (g)
Malic acid	$4LiCoO_2$(s) + $12C_4H_6O_5$ (as) $\rightarrow$ $4LiC_4H_5O_5$ (aq) + $4CoC_4H_5O_5$ (aq) + $6H_2O$ (l) + O_2 (g)
Ascorbic acid	$4C_6H_8O_6 + 2LiCoO_2 \rightarrow C_6H_6O_6 + C_6H_6O_6Li_2 + 2C_6H_6O_6Co + 4H_2O$
Acetic acid	$Li_2CoMn_3O_8$(s) + $10CH_3COOH$(aq) + $10H_2O_2$(aq) $\rightarrow$ $2CH_3COOLi$(aq) + $Co(CH_3COO)_2$(aq) + $3Mn(CH_3COO)_2$ (aq) + $8H_2O$ + $3O_2$

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- Y. Kikuchi, T. Ichikawa, M. Sugiyama, and M. Koyama, "Battery-assisted low-cost hydrogen production from solar energy: Rational target setting for future technology systems," Int. J. of Hydrogen Energy, Vol. 44, Issue 3, pp. 1451-1465, 2019.
- Y. Kikuchi, Y. Kanematsu, N. Yoshikawa, T. Okubo, and M. Takagaki, "Environmental and resource use analysis of plant factories with energy technology options: a case study in Japan," J. of Cleaner Production, Vol.186, No.10, pp. 703-717, 2018.

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- A. Heiho, Y. Kanematsu, M. Nagase, S. Murakami, C. Tokoro, and Y. Kikuchi, “Life Cycle Assessment of Resource Recovery from Waste Electrical and Electronic Equipment: A Case Study of Tantalum Recovery by Chain-Using Drum-Typed Impact Mill,” Kagaku Kogaku Ronbunshu, Vol.45, No.6, pp. 244-252, 2019 (in Japanese).
- A. Heiho, H. Hondo, and Y. Moriizumi, “Social Life Cycle Assessment of Biomass Projects Focusing on Employment Changes in Regions,” J. of the Japan Institute of Energy, Vol.95, No.2, pp. 159-169, 2015 (in Japanese).

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- Y. Dou, T. Togawa, L. Dong, M. Fujii, S. Ohnishi, H. Tanikawa, and T. Fujita, “Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: A case in Fukushima, Japan,” Resources Conservation and Recycling Vol.128, pp. 406-416, 2018.
- Y. Dou, M. Fujii, T. Fujita, K. Gomi, S. Maki, and H. Tanikawa, “Potential of Waste Heat Exchange Considering Industrial Location Changes: A Case of Shinchi-Soma Region in Fukushima, Japan,” J. of Japan Society of Civil Engineers, Ser. G (Environmental Research), Vol.73, Issue 6, pp. II_353-II_363, 2017.

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- I-C. Chen, Y. Kikuchi, Y. Fukushima, H. Sugiyama, and M. Hirao, "Developing Technology Introduction Strategies Based on Visualized Scenario Analysis: Application in Energy Systems Design," Environmental Progress & Sustainable Energy, Vol.34, No.3, pp. 832-840, 2015.
- I-C. Chen, Y. Fukushima, Y. Kikuchi, and M. Hirao, "A graphical representation for consequential life cycle assessment of future technologies. Part 1: methodological framework," Int. J. of Life Cycle Assessment, Vol.17, No.2, pp. 119-125, 2012.

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Main Works:

- J.-Q. Lu, S. Kumagai, H. Ohno, T. Kameda, Y. Saito, T. Yoshioka, and Y. Fukushima, "Deducing targets of emerging technologies based on ex ante life cycle thinking: case study on a chlorine recovery process for polyvinyl chloride wastes," Resources, Conservation & Recycling, Vol.151, 104500, 2019.
- Y. Fukushima and S.-P. Chen, "A decision support tool for modification in crop cultivation method based on life cycle assessment: A case study on greenhouse gas emission reduction in Taiwanese sugarcane cultivation," Int. J. of Life Cycle Assessment, Vol.14, No.7, pp. 639-655, 2009.
- Y. Fukushima, M. Shimada, S. Kraines, M. Hirao, and M. Koyama, "Scenarios of solid oxide fuel cell introduction into Japanese society," J. of Power Sources, Vol.131, Nos.1-2, pp. 327-339, 2004.
- "Modeling the Special Dynamics of Robotic Manipulators with Flexible Links and Joint Clearances," ASME J. of Mechanical Design, Vol.115, pp. 839-847, 1993.

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Main Works:
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- "Mechanism and kinetics of enhancement of cerium dissolution from weathered residual rare earth ore by planetary ball milling," Minerals Engineering, Vol.134, pp. 365-371, 2019.
- "Investigation and evaluation of the detachment of printed circuit boards from waste appliances for effective recycling," Waste Management, Vol.78, pp. 474-482, 2018.
- "Sorption mechanisms of chromate with coprecipitated ferrihydrite in aqueous solution," J. of Hazardous Materials, Vol.334, pp. 142-149, 2017.
- "Sorption Mechanisms of Arsenate during Coprecipitation with Ferrihydrite in Aqueous Solution," Environmental Science and Technology, Vol.44, No.2, pp. 638-643, 2010.
- "Modeling the Special Dynamics of Robotic Manipulators with Flexible Links and Joint Clearances," ASME J. of Mechanical Design, Vol.115, Issue 4, pp. 839-847, 1993.

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- Science Council of Japan (SCJ), Council Member
- Engineering Academy of Japan (EAJ)
- Mining and Materials Processing Institute of Japan (MMIJ)
- Society of Chemical Engineers, Japan (SCEJ), Director
- Society of Powder Technology, Japan (SPTJ), Director
- EcoDesign Promotion Network, Director