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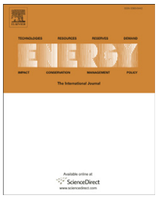

Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels

Kishore Ganesan, M.Sc Environomical Pathways for Sustainable Energy System. [a, b], César Valderrama, Dr. Associate Professor at UPC, BarcelonaTECH [a, b, c, *]

[a] Barcelona School of Industrial Engineering, ETSEIB, UPC·BarcelonaTECH, Spain
[b] Chemical Engineering Department, Universitat Politècnica de Catalunya UPC·BarcelonaTECH, Spain
[c] Barcelona Multi-Scale Science and Engineering Research Center, BarcelonaTECH, Spain

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ABSTRACT

In this research, a framework for performing Anticipatory Life Cycle Analysis (a-LCA) has been developed to identify the sustainable end of life (EoL) management option for crystalline silicon photovoltaic (PV) panels. a-LCA can be used to stimulate proactive and sustainable decision making for emerging technologies through stakeholder participation. In this research, stakeholders related to EoL management of PV panels participated through a survey to identify and prioritize economic, environmental, and social indicators for PV EoL management. Several EoL strategies like bulk material recycling (centralized and decentralized), high value material recycling, and landfilling were chosen and assessed for the prioritised sustainability indicators. The EoL strategies were then ranked through a multi-criteria decision analysis tool for their level of sustainability.

High value material recycling (close to 100% material recovery) was identified as the most sustainable option followed by bulk recycling of PV panels that recover only the major constituents, such as aluminium, glass, and e-waste. Landfilling remained the least preferred option, although it currently has an economic advantage over other recycling options, highlighting the need to shift the user preferences. The developed a-LCA framework is iterative and can be applied by decision makers for different EoL management strategies in the future.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), accelerated deployment of renewables combined with deep electrification and increased energy efficiency can reduce 90% of energy-related carbon dioxide (CO_2) emissions by 2050 and limit the rise in the global temperature to well below 2 °C and closer to 1.5 °C compared to pre-industrial levels [1]. Solar photovoltaics (PV) has been one of the fastest-growing renewable energy technologies owing to its cost competitiveness and abundance of sunlight resources across the world. It is estimated that solar PV capacity would have to reach 2840 GW by 2030 and eventually 8519 GW by 2050 to reduce one-fifth of the total emissions in 2050. Thus, PV installations are bound to be thirteen times higher by 2050 than the current value of 635 GW in 2019. Also, solar PV is forecasted to represent 25% of the world electricity generation mix by 2050 compared to the current share of 3% in 2019 [2].

PV panels have a product warranty and performance warranty. The product warranty deals with the non-conformity of modules resulting from defects in materials and workmanship under normal applications, installations, use, and service conditions specified by the manufacturer's standard product documentation. On average, the product warranty for PV modules is around ten years. Through the performance warranty, the manufacturer generally guarantees not less than 98% of the labelled power output in the first year and an annual power decline of no more than 0.55%, meaning that at the end of 25 years, the module should be performing no less than 84.8% of the labelled power output. Therefore, c-Si PV panels have a nominal service life or a technical lifetime of 25 years, and nowadays, some premium manufacturers have extended it to 30 years. The actual service life of c-Si PV panels could vary from 0 to 50 years [3]. Therefore, according to the PV module manufacturers, c-Si PV

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[*] Corresponding author. Universitat Politècnica de Catalunya UPC, Spain.
E-mail addresses: kishoreganesh18@gmail.com, kishore.ganesan@estudiantat.upc.edu (K. Ganesan), cesar.alberto.valderrama@upc.edu (C. Valderrama).

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Nomenclature

a-LCA	Anticipatory Life Cycle Analysis
ANSI	American National Standards Institute
c-Si	Crystalline Silicon PV panels
CdTe	Cadmium Telluride
CIS	Copper Indium Selenium
CO/CO_2	Carbon Monoxide/Carbon Dioxide
EPR	Extended Producer Responsibility
EVA	Ethylene Vinyl Acetate
FRELP	Full Recovery End of Life Photovoltaic
GHG	Green House Gases
GW	Giga Watts
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
ITRPV	International Technology Roadmap for Photovoltaic
JPEA	Japan Photovoltaic Energy Association
KOPIA	Korea Photovoltaic Industry Association
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Variable Theory
MCDA	Multi Criteria Decision Analysis
MG	Metallurgical Grade
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment, Forest and Climate Change
MTA	Metric Ton per Annum
MW	Mega Watts
NREL	National Renewable Energy Laboratory
PRO	Producer Responsibility Organization
PV	Photovoltaic
PVC	Poly Vinyl Chloride
PVF	Poly Vinyl Fluoride
PVPS	Photovoltaic Power Systems
R&D	Research and Development
SDG	Sustainable Development Goals
TERI	The Energy and Research Institute
TRL	Technology Readiness Level
TW	Tera Watts
UK	United Kingdom
UN	United Nations
WEEE	Waste Electrical and Electronic Equipment

panels are classified as waste if the maximum power loss is higher than 20% less than the labelled power output [4].

Although a significant number of installed c-Si PV panels have not reached their end of life, there are reported PV waste flows due to breakages or early losses, as reported previously. According to the International Renewable Energy Agency (IRENA), 0.043 and 0.25 million tonnes of global PV waste could have been generated in 2016 based on early loss and regular loss scenarios, respectively. IRENA forecasts that 60–78 million tonnes of PV waste would be generated by 2050. The top five waste generation countries by 2050 would be China, the US, Japan, India, and Germany. The PV waste volumes translate to secondary raw material content that could produce 2 billion new panels and US Dollars (USD) 15 billion by value [5]. It is estimated that 80% of the current PV waste stream consists of product defects upon production, transportation, or infant failures over the first four years of operation than the products that reach the end of their technical life [6]. Field experience indicates typical PV module failure rates of ~0.15–0.25% per year, meaning that approximately 2% of a PV plant's entire fleet is predicted to fail after 11–12 years. Hence, it is clear that although PV modules have a long life time, the preparation for a sustainable end of life management is undeniable given the volume of installations currently and the exponential increase expected in the future.

The existing policies/regulations related to PV waste management are depicted in Fig. 1. The countries in blue have already implemented Extended Producer Responsibility to manage end of life PV panels, whereas the countries in orange are in the process of implementing a policy specific to PV waste disposal. The rest of the countries do not have specific solar PV waste regulations, with PV panels currently treated under the general waste category.

While analysing the waste management strategies with respect to PV panels in the literature, it could be found that prevention of PV waste is being carried out through the development of standards like American National Standard, NSF/American National Standards Institute (ANSI) 457 Sustainability Leadership Standard for Photovoltaic Modules, Cradle to Cradle certification, Solar scorecard by Silicon Valley Toxic Coalition, and media initiatives like PV magazine's UP [6]. On the reuse front, according to IRENA [5], 80% of the PV waste stream can contain defects from the first four years of operation or production or transportation. It is believed that 45–65% of these waste modules can be refurbished or repaired. Currently, the reuse and repair/refurbishment of PV modules remain informal and are neither systemized nor standardised. Private companies currently undertake such repair services without any support from the original manufacturers. Second life PV modules currently do not have characterization, reliability testing, certification, or labelling standards. Repair and refurbishment can be a ready option if the PV panel failure is due to defective frames and mounting clamps, faulty bypass diodes, defective wire connectors in junction boxes, and Potential Induced Degradation (PID) [6].

Recycling of photovoltaic solar modules has been in research since the end of the 90s, with the first patent filed for c-Si PV panel recycling in 1995 [7]. There has been more emphasis on research and development for recycling thin-film modules like cadmium telluride (CdTe) due to the hazardous and rare earth elements content in the modules.

Although most PV module installations have been made up of crystalline silicon, there is only one commercial standalone PV recycling facility compared to thin-film modules. The generated PV waste is currently processed in laminated glass/metal recycling centres due to a lack of economic feasibility. It is also reported that waste PV panels are currently disposed in landfills, and recent reports indicated an instance of waste PV panels in Italy being smuggled into African and Middle Eastern markets [8]. Recovered raw materials from solar panel waste can satisfy growing installation demand, mitigate price fluctuations in PV manufacturing, and increase energy security [9].

The c-Si PV recycling technology has been researched extensively in the literature, with 128 patents registered across the world [7]. The most critical step in the process is the delamination of the polymer (ethylene vinyl acetate (EVA)) sheets from the silicon panel core in PV recycling. Initially, the junction box and the aluminium frames are removed by mechanical detachment from the c-Si PV panels. The delamination treatments can be broadly classified as mechanical, thermal, and chemical, as shown in Fig. 2 [10].

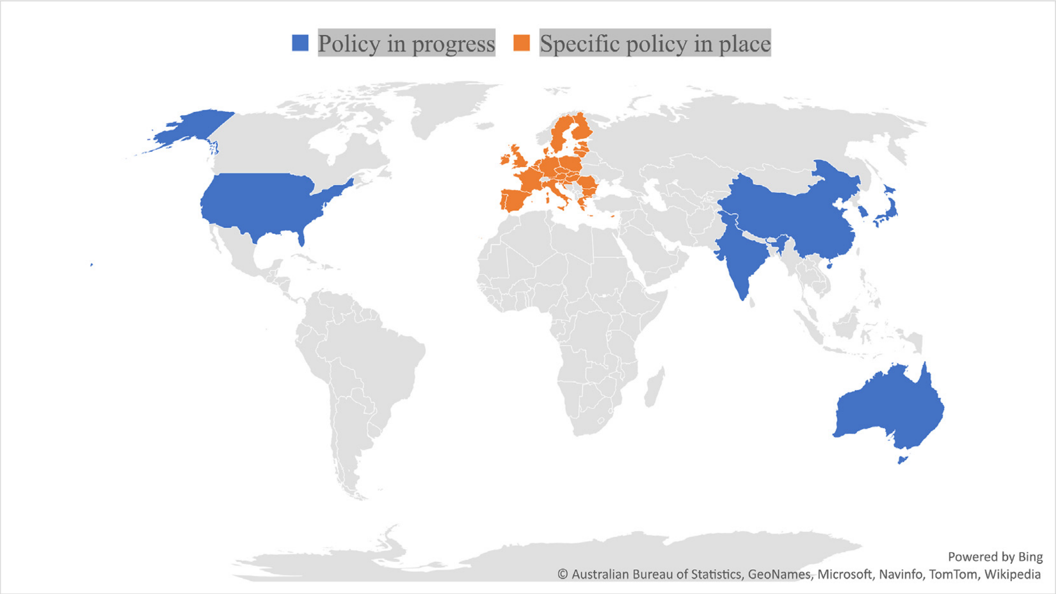

Fig. 1. Status of available policies for End of Life Management of Solar PV panels.

Mechanical delamination with the aluminium frame and junction box removal has been the most used technology commercially for PV recycling. Glass, aluminium, and e-waste are the recovered materials through purely mechanical processes. Such processes exhibit low energy demand and easy integration with the existing glass/metal/e-waste recycling infrastructure. Silicon and other metals, such as silver, copper, lead, and tin, are difficult to separate in such processes without chemical treatments. As recovery targets mandated by Waste Electrical and Electronic Equipment (WEEE) legislation have been set as a percentage of the overall weight of PV

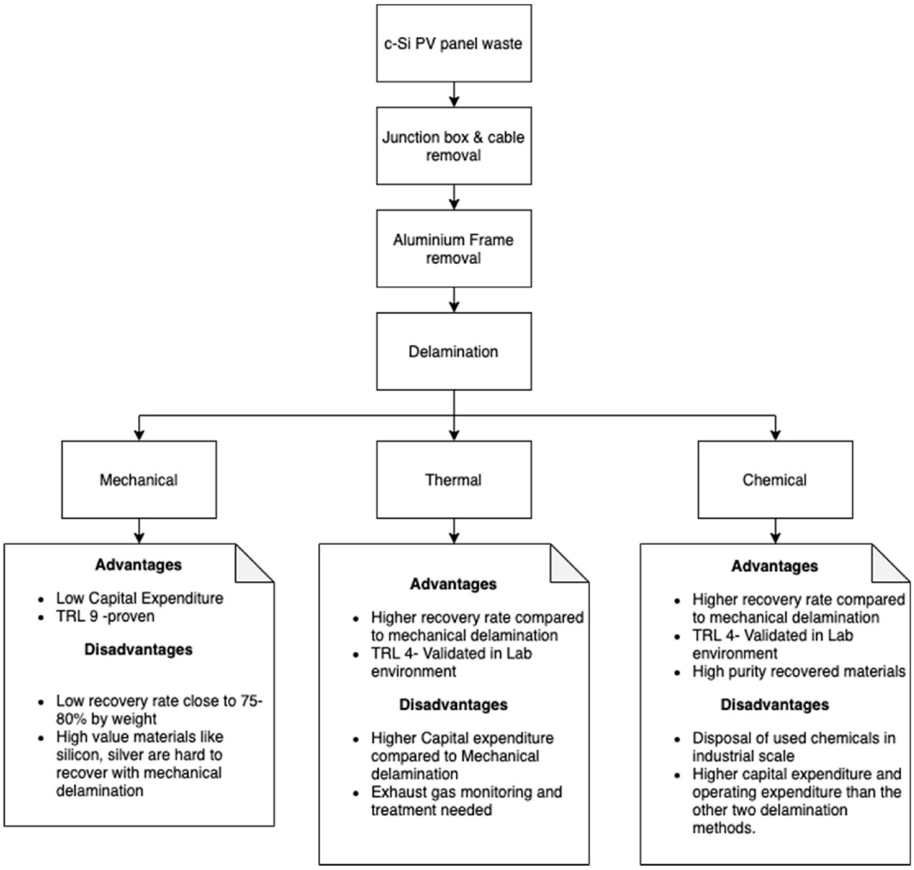

Fig. 2. Different delamination technologies for crystalline silicon (c-Si) panel recycling.

modules, such mechanical treatment of panels is sufficient to achieve the same given that glass and aluminium alone contribute to 88% of the PV module by weight. Therefore, high-value materials like silicon and silver and hazardous materials like lead are currently not recovered due to their minor presence by weight in c-Si PV panels and are disposed of as a mixture in landfills after processing [11].

Thermal delamination methods enable pure material stream recovery of glass and PV core containing silicon and metals as the polymer sheets undergo complete pyrolysis or burn off. Most of the commercially used back sheet materials contain fluorine. According to the literature, such back sheets are removed in most cases before the thermal delamination occurs. This is beneficial because combustion of halogenated polymers makes exhaust gas treatment necessary. Also, as a result of thermal delamination, metallic contacts present in PV cells might melt and diffuse at high temperatures into other recovered components, such as glass and silicon wafers. Thus, purification steps are necessary for the recovery of high purity silicon. There is also a research gap for examining the energy recovery potential from exhaust gases during thermal delamination. It is to be noted that recycling processes involving such thermal-based methods are yet to be scaled commercially [12].

Chemical delamination methods involve the dissolution of EVA in organic or inorganic solvents. The treatment time initially ranged in days, but dissolution under ultrasonic irradiance has enabled shorter dissolution times. Chemical delamination is still at the laboratory stage, and there is a need to understand the additional environmental impact due to the inclusion of chemical solvents [13].

Material recovery of c-Si PV recycling, in general, has improved from 60% in 1998 to 99% in 2020 by weight. Therefore, the next expected development would be the scaling up of lab/pilot level recycling processes to the commercial level [11]. It is clear from the literature [14] that chemical treatments are necessary to recover the trace metal constituents of PV cells irrespective of the delamination method. Different methods reported in literature for mechanical, thermal, and chemical delamination methods along with the chemical treatments necessary to recover trace metals are depicted in section S.1 in the Supplementary Material.

Thus, studying the environmental impact due to the recycling process becomes significant. A discussion on the design for recycling has also picked up with certain PV manufacturers focusing on discarding hazardous (lead) and high value (silver) metal contents from future PV modules [15]. c-Si PV panels do not produce direct emissions compared to other conventional energy sources. However, they do have emissions associated with their raw material sourcing, manufacturing (upstream), and end of life phase (downstream) in their entire life cycle [16]. Therefore, to maintain the integrity of showcasing PV panels as green products, the PV manufacturers ought to sustainably streamline the processes involved in their products' life cycle. Many life cycle assessment (LCA) studies have been conducted on PV panels, which have outlined the environmental hotspots in PV manufacturing and have compared various types of PV panels for their energy payback time, greenhouse gas (GHG) emission, and cumulative energy demand across geographies [17].

PV recycling technologies are still in their nascent stage with their validation at the lab and pilot scales. There is also a dearth of data available on PV panel processing at the end of life stage. The existing LCA framework is mostly retrospective with the expectation of detailed data, which is obtainable only from mature systems/technologies. Therefore, traditional LCA is limited for assessing emerging technologies, providing timely information to decision-makers, and guiding the future growth of rapidly evolving technologies. Traditional LCA also disregards the importance of stakeholder engagement for critical modelling decisions, thus affecting responsible research and innovation [18].

Prospective LCA methods are being developed to include assessment of processes with a high degree of uncertainty. As opposed to the existing LCA framework where a practitioner makes decisions in isolation, prospective LCA employs social science engagement methods to identify impacted stakeholders and elicit their value preferences to inform modelling decisions.

Anticipatory LCA was created as a forward-looking, non-predictive tool that increases model uncertainty by including prospective modelling tools and social perspectives. Anticipatory LCA (a-LCA) has been carried out for emerging technologies like photovoltaics [19], nanoparticles [20], and lithium-ion batteries [21] and to enable future sustainable construction [22]. Although recommendations have been made to carry out a-LCA for EoL management of c-Si PV panels [23], no study on a-LCA has been reported yet, especially for c-Si PV modules.

A summary highlighting the various LCA studies reported on PV panels are collected in Table 1.

Based on to the literature reviewed, the following research gaps have been identified: i) limited number of LCA studies have been reported on recycling of c-Si PV panels [9]. The reason has been attributed to dearth of data and with the current status of PV recycling centres being at lab/pilot stage; and ii) anticipatory LCA framework have enabled assessment of emerging technologies through LCA and have helped in facilitating proactive decision making for creating a sustainable technology or process. However no anticipatory LCA framework or studies have been conducted on end of life management of c-Si PV panels.

This research work is the first of its kind to develop an a-LCA framework for EoL management of c-Si PV panels. In addition, it also differs from previous reported LCA studies because it involves stakeholder participation and feedback right from the selection of the functional unit to the prioritization of environmental impact categories. Furthermore, economic and social dimensions have also been considered in order to provide a sustainable EoL management scenario for c-Si PV panels.

The goal of this study was to conduct an a-LCA to visualize an efficient, economic, and eco-friendly process flow/stream for EoL management of c-Si PV panels. The a-LCA method was applied to lab/pilot scale data of c-Si PV recycling technologies to identify and inform recyclers on environmentally improved pathways, minimize the energy impacts, and forecast PV recycling scenarios through stakeholder engagement. The developed a-LCA framework is iterative and can be used by stakeholders in the future to compare various waste management scenarios with different sustainability indicators.

2. Methodology

A general interdisciplinary framework to perform a-LCA, indicating the material and knowledge flows and the actors needed for the analysis, was proposed by Wender et al. [29]. This framework has been adapted to carry out the a-LCA on c-Si PV recycling processes, as shown in Fig. 3. The framework involves stakeholder participation to identify the relevant waste management strategies and to fix the system boundary for LCA. This is followed by a stakeholder engagement exercise in order to identify and prioritize sustainability indicators, which are derived from Sustainable Development Goals (SDGs). The sustainability indicators, which can be broadly classified into environmental, economic, and social indicators, can be quantified through tools like LCA, stakeholder interviews, feasibility analysis, etc. The final part of the framework involves quantification of the waste management strategies using

Table 1
Summary of the LCA studies reported in literature on PV panels.

Study	Location	PV panel type	Functional Unit	System Boundary
				Retrospective life cycle analyses
Kim et al. [24]	Korea	c-Si PV panel	1 kWh	Cradle to Grave (From raw material extraction to recycling of PV panels).
Fu et al. [25]	China	c-Si PV panel	1 kWh	Cradle to Gate (From raw material extraction to use of PV panels)
Latunussa et al. [26]	Italy	c-Si PV panel	1000 kg waste PV panel	Only the recycling stage with data from FRELP project.
Stolz et al. [27]	Global	c-Si PV panel and CdTe PV panel	1 kg of waste PV panel	Only the recycling stage of PV panel with data from the widely adopted recycling technologies as a part of IEA PVPS task 12.
				Prospective/Anticipatory life cycle analysis
Ravikumar et al. [28]	United States of America	CdTe panel	1 kg of waste PV panel	Anticipatory approach to quantify the energy flows in recycling CdTe panels.

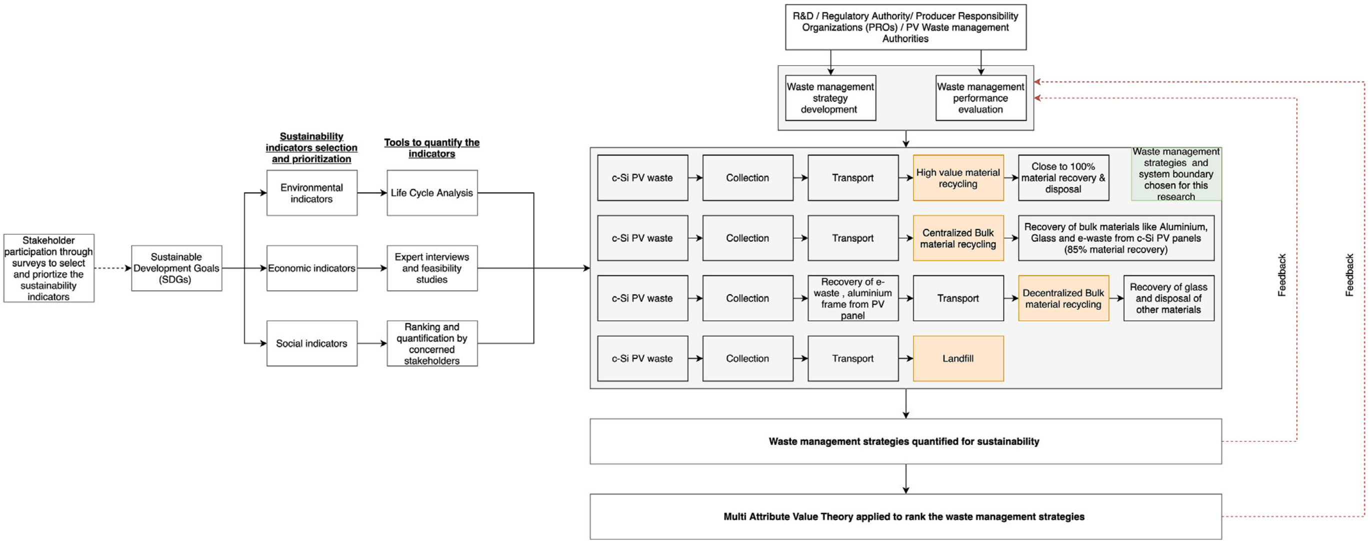

Fig. 3. *a-LCA methodology used for c-Si PV recycling (adapted from Wender* et al. [29]).

sustainability indicators and ranking of the quantified waste management strategies through multi-criteria decision analysis. The sustainability scores can be sent as a feedback to the waste management strategists and process developers who can hone the waste management process in order to achieve a higher sustainability score. This makes the a-LCA framework an iterative process, which can ensure proactive decision making for emerging technologies to be designed in a sustainable manner.

For the stakeholder engagement in this research, an online survey was carried out to obtain prioritization on various sustainable impact categories to analyse end-of-life management of c-Si PV panels. Combining the results from LCA and the weighting of impact factors from the stakeholders, multi-attribute value theory was carried out, and the ranking of chosen alternatives was performed. The analysis results can be used by PV recycling technology developers to streamline their processes environmentally and economically. Research funders can start focusing on new technologies to satisfy the priorities of their stakeholders of interest based on this analysis.

The following sections highlight the various aspects involved in the a-LCA framework to identify the sustainable waste management strategy for c-Si PV panels. Section 2.1 discusses the methodology involved in stakeholder engagement to identify and prioritize the sustainability indicators. Section 2.2 involves life cycle analysis assumptions and methodology, while section 2.3 highlights the multi-criteria decision analysis needed to rank the waste management strategies.

2.1. Stakeholder engagement through an online survey

Stakeholder engagement was performed through an online survey via a Google form (included in Section S.2 in the Supplementary Material). The questionnaire contents were prepared after referring to literature and finalised after discussion with the stakeholders. The detailed questionnaire was aimed at PV module manufacturers, component manufacturers, recyclers, academicians, consultants, non-governmental organizations (NGOs), regulatory authorities, and end-users. The aims of the survey were: i) to find the interest of organizations on EoL management of c-Si PV panels; ii) to obtain stakeholder opinions on PV panel lifetime and material intensity in the near future; iii) to understand the perspective of stakeholders on the drivers, barriers, and enablers to manage EoL panels; iv) to obtain stakeholders' preferences about economic, environmental, and social parameters to determine sustainable waste management strategies for c-Si PV panels.

The survey was divided into seven sections, including an introduction, PV module trends, drivers, barriers, enablers to EoL management of PV panels, sustainability criteria selection for a-LCA, and nomination. Some of the sections were shared based on their relevance to the type of organization of the respondent, e.g., the section on c-Si PV module trends was introduced only to PV manufacturers, module component suppliers, and researchers.

The survey was distributed to leading PV manufacturers, component suppliers, end-users of solar PV (power plant owners), and recyclers. It was also sent to notable stakeholders across the world who were already associated with the EoL management of c-

Si PV panels via personal invites through social media platforms.

The section for sustainability criteria selection contained a brief explanation of the planned scenarios for the EoL management of c-Si PV panels. SDGs and targets are deemed useful in assessing the three sustainability dimensions: environmental, economic, and social. An indicator traceability model was developed to select the various sub-criteria for assessment under the three sustainability dimensions, as shown in Fig. 4. The model depicts the traceability from the overall objective of sustainable EoL management of c-Si PV panels to relevant SDG goals, then to underlying targets, which finally lead to measurable indicators [30].

Based on Fig. 4, the various sustainability indicators selected for the survey assessment are listed in Table 2.

2.2. LCA to quantify the environmental impacts

The scope of the LCA on recycling EoL c-Si PV panels was defined as gate to gate within a system boundary that includes collection and transportation of waste followed by the recycling process. The functional unit in this study is defined as 1 ton of c-Si PV waste collected and recycled within the period of study in 2020 and the geographical location in India. The composition of the panel reported in the literature [32] was modified to include cables and junction boxes. Details can be found in Section S.3 (Supplementary Material). The EoL or avoided burden modelling approach was used for this study. In this approach, the recycling impact is fully allocated to the product using recycled material. No burdens from the recycling process are allocated to the upstream product [33]. The EoL approach is recommended to be used when identifying the environmentally preferable EoL treatment option of products (gate to gate) [34]. In this study, the impacts of various recycling processes for c-Si PV panels can be separately studied. The benefits of recycling are calculated as the avoided burden in primary production due to the recovered secondary materials stream from the corresponding recycling processes [35]. The system boundary of the performed LCA is detailed in Fig. 5.

The chosen LCA software for the analysis was OpenLCA version 1.10.3, and the auxiliary datasets were obtained using the Ecoinvent 3.6 database. The environmental impact assessment method used was ReCiPe Midpoint (H). The selection of impact category indicators was intended to facilitate the comparison of results with the reported literature. The various waste management processes considered for this study are detailed in Table 3. The c-Si PV waste was initially assumed to be transported 400 km to a PV recycling facility in Tamil Nadu, India. The facility was assumed to be located in an industrial area. Hence, the downstream material recyclers, secondary raw material producers, and disposal sites are assumed to be located around 50 km from the PV recycling centre.

Assumptions:

- All the above-reported recycling processes were assumed to treat 1000 kg c-Si PV modules by proportionally scaling up the consumables requirements of those processes that were reported on the lab scale.
- The datasets of all the processes were tailored to match or stay relevant to the environment in India. Mostly, the regionalized process datasets for India were chosen for this analysis. A broader global oriented process dataset was chosen to carry out the LCA only when the regionalized datasets were unavailable.
- For landfilling, as data specifically for PV panels were unavailable in the literature, the datasets representing the various individual materials embedded in 1 ton of PV waste were considered.
- The secondary raw material production of aluminium and copper was assumed to have 90% efficiency, and benefits are reported after taking into account the transport of scrap to the secondary raw material production facility and the impact of processing of the scrap on the secondary raw materials.
- Silver that was recovered from the FRELP PV recycling process was assumed to be of a quality that could be directly substituted for the primary material.
- Solar grade silicon recovered from the PV recycling process was downcycled to be used as metallurgical grade silicon.
- Glass cullets were assumed to be used for various glass production depending on their quality. Intact glass recovered from chemical treatment is directly used as solar glass, whereas glass

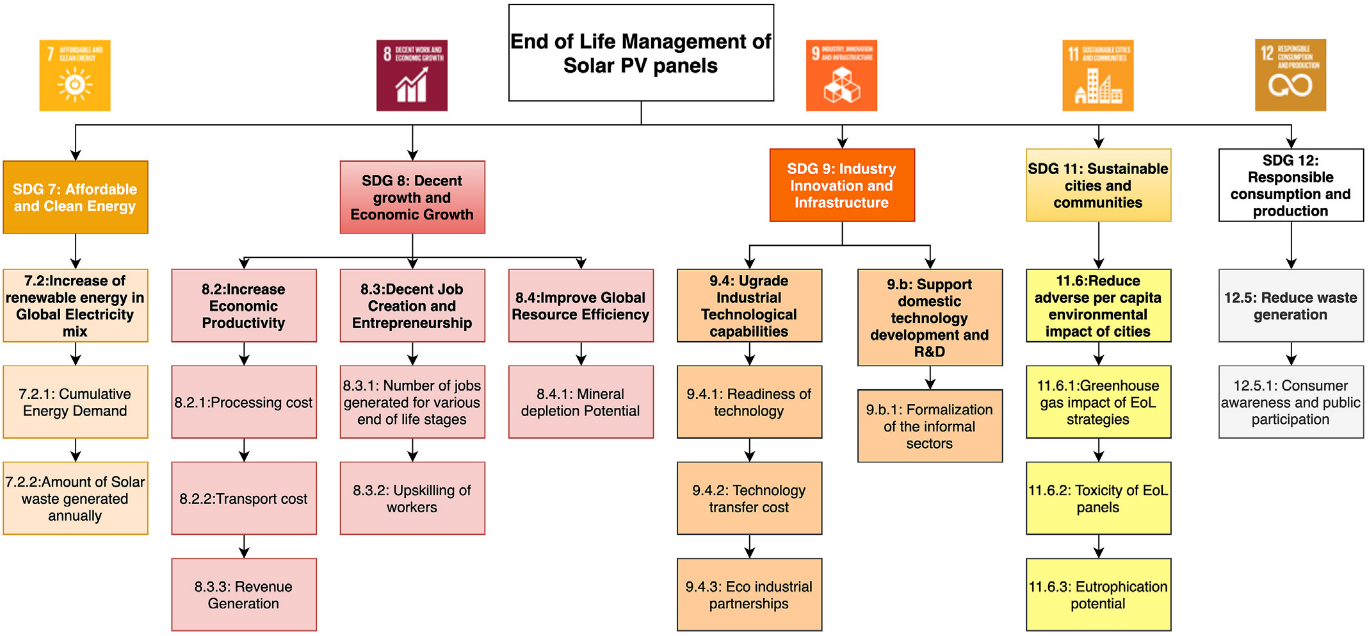

Fig. 4. Indicator traceability model for EoL management of c-Si PV panels [31].

Table 2
Selected assessment criteria to compare EoL alternatives.

Assessment Criteria	Unit	Description	Relevant SDG	Goal	Calculation Method
		Environmental Impact			
Greenhouse Gas Emissions	$kgCO_2e$	Carbon emissions of various processes	11.6	minimize	LCA
Cumulative Energy Demand	MJ	Total amount of energy (fossil-based) used to complete the process	7.2	minimize	LCA
Human(Material) Toxicity	kg 1.4DBeq	Toxicity of materials to human health involved or as a result of the process used	11.6	minimize	LCA
Metal Depletion	kg Fe eq	Potential of metal depletion as a result of EoL management used	8.4	minimize	LCA
Eutrophication Potential	kg P eq	Eutrophication potential caused by EoL alternative to the marine environment	11.6	minimize	LCA
		Economic Impact			
Processing costs	€/ton	The total cost incurred to the EoL product processor excluding transport cost	8.2	minimize	Literature
Transport cost	€	The cost incurred for the transportation of waste	8.2	minimize	Literature
Readiness of Technology	TRL	The suitability of the adopted technology to operate on a commercial scale	9.4	maximize	Literature
Revenue Generation	€/ton	Revenue obtained from material or energy recovery	8.2	maximize	Literature
Technology Transfer cost	Ranking	The resource cost of transferring technological know-how	9.4	minimize	Literature
		Social Impact			
Consumer awareness and public participation	Ranking	Involvement of end-user to initiate the EoL management alternative	12.5	maximize	Stakeholder interview
Job creation	Number	Direct employment opportunities caused by EoL management alternative	8.3	maximize	Stakeholder interview
Eco-industrial partnership	Ranking	Possibility of industrial symbiosis	9.4	maximize	Stakeholder interview
Formalizing of informal sectors	Ranking	Potential of EoL alternative to formalize the informal sector	9.b	maximize	Stakeholder interview
Upskilling of workers	Ranking	EoL management alternative promoting skill sets of workers	8.3	maximize	Stakeholder interview

cullets from the FRELP process are used for flat glass production. The cullets from other mechanical delamination are used for fibre wool glass production, as they are assumed to be contaminated with traces of metals.

- Secondary copper cathodes and aluminium ingots are assumed to replace the 100% primary production scenario to calculate the credits for recycling PV panels. For glass cullets, the amount of primary raw materials and energy that have been displaced by the cullets is calculated as credits.
- The residue or waste present in the respective recycling processes is assumed to be properly landfilled or incinerated.

2.3. *Multi-attribute value theory*

Different EoL management alternatives/strategies were ranked based on environmental, economic, and social indicators as the last part of the a-LCA of c-Si PV panels. The indicators were prioritised through the stakeholder survey and quantified for each of the alternatives or waste management strategies using LCA, expert interviews, and literature reviews. The objective is to identify the most appropriate EoL management alternative for c-Si PV panels.

The different EoL management alternatives taken into consideration in this study are: i) Bulk recycling (centralized), ii) Bulk recycling (De-centralized), iii) High-value recycling (close to 100% material recovery) using FRELP, and iv) Disposal of c-Si PV panels in the landfill.

Multi-attribute value theory (MAVT) is utilized in the current study due to its suitability for participatory processes and flexibility. Both quantitative and qualitative data based on expert judgment can be handled by the MAVT method [31]. DECERNS MCDA is a Multi-criteria decision analysis (MCDA) software in which various multi-criteria methods like MAVT can be implemented [36].

The various EoL management alternatives for c-Si PV panels chosen for this study are modelled in the DECERNS MCDA software. Each sustainability indicator is quantified against a given alternative/EoL management technique. Weights provided for each of the indicators from the stakeholder consultation are then assigned, and ranking of the EoL management alternatives is done. A sensitivity analysis is also performed to check the robustness of the model outcome.

3. Results and discussion

a-LCA was carried on the EoL management of c-Si PV panels by ranking various waste management strategies using environment, economic, and social indicators prioritised through stakeholder consultations and obtained through a-LCA, literature, and expert interviews. Section 3.1 depicts the results from the online survey conducted for stakeholder engagement for selection and prioritization of the sustainability indicators for a-LCA. Section 3.2 is focused on quantification of the chosen sustainability indicators for each of the waste management strategies and ranking of the waste management strategies through MAVT. A sensitivity analysis is carried out on the obtained results in order to check the robustness of the created a-LCA model in Section 3.3.

3.1. *Stakeholder engagement through an online survey*

The survey conducted via a Google form garnered **79 responses** from experts related to waste management and the solar photovoltaics industry. The survey distribution was done through personal invitation via email, social media interaction, and distribution in virtual conferences, e.g., PV magazine roundtable. Detailed information on the survey participants and on sections of survey that focused on trends, drivers, barriers and enablers can be found in Section S.4 (Supplementary Material).

The survey introduced the respondents to the various waste management strategies possible with c-Si PV panels, which included disposal of c-Si PV panels and two recycling strategies, as follows: i) transporting PV waste to a centralized recycling location,

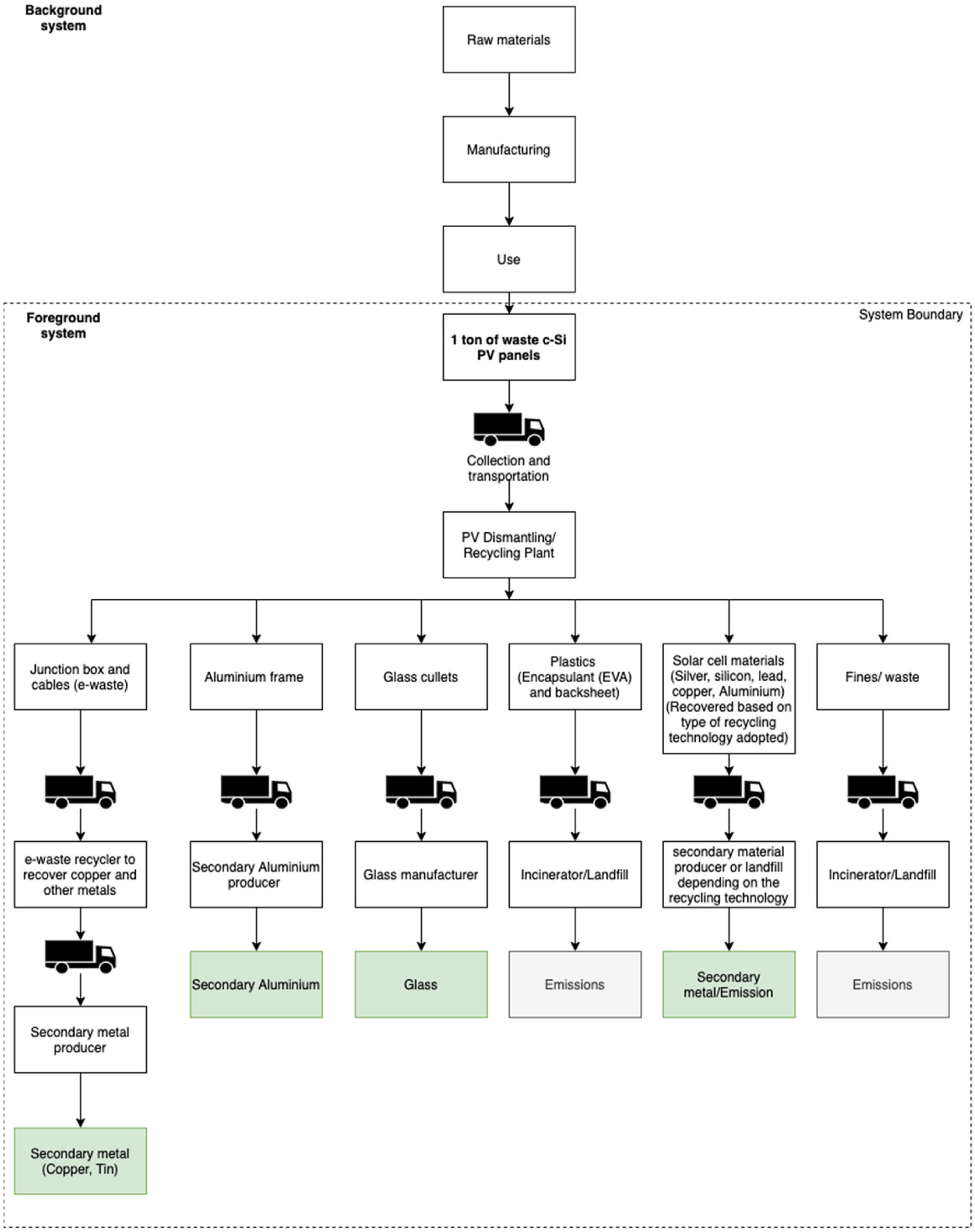

Fig. 5. System Boundary for a-LCA of c-Si PV solar panels.

which can extract both bulk (glass, aluminium) materials and high value (silver) materials; and ii) decentralized/distributed/mobile recycling plants to perform bulk recycling followed by transportation to a centralized facility that performs high-value recycling after sufficient accumulation of the processed waste.

These recycling strategies are apart from the technology variation involving the delamination of c-Si PV panels. In order to assess the various waste management strategies, practical indicators were developed through stakeholder interaction and literature review with SDGs as a base, which is detailed in methodology section 2.1 and Fig. 4. All those indicators or sub-criteria were classified under three main criteria that represented planet, profit, and people as sustainability dimensions, namely environmental, economic, and social impacts, respectively.

After going through the waste management strategies, the respondents rate the criteria (economic, environmental, and social) on a three-point scale (less, medium, and most important) and sub-criteria on a five-point scale (not important, less important, important, more important, and most important). The qualitative scale was chosen for better understanding of the survey respondents [31].

This section's survey results were quantified through the weighted average method by assigning three-point scale sustainability dimension ratings based on literature [31]. The mean, standard deviation, and weights rated by 79 survey participants against the criteria and sub-criteria are specified in Table 4.

Table 3
EoL Management options for c-Si PV panels considered in this study.

Name	Level	Background	Process	Reference
Bulk Centralized recycling	Pilot	Data from a PV recycling pilot plant in India with 2.5 ton/day capacity was used. Centralised Bulk recycling refers to collection and transport of PV panel as a whole to a recycling centre whereas	State of the art mechanical delamination method involving shredding, crushing, and sorting of PV panels to recover glass cullets, aluminium frame, and e-waste	Measured and recorded at Pilot plant premises
Bulk Decentralized recycling	Pilot	Decentralized Bulk recycling refers to removal of aluminium frame, junction box, cable at the waste generation site and transporting the rest of the PV panel content to the recycling centre.		
High Value recycling process (FRELP)	Pilot	FRELP is an EU Life project developed to pilot a crystalline silicon PV panel recycling process that potentially achieves close to 100% material recovery	FRELP involves the delamination of glass from the PV panel through hot knife cutting followed by incineration to separate solar cell materials from plastics (EVA + back sheets). The recovered ash is then chemically treated to recover silver, aluminium, and silicon.	[32]
			Disposal	
Landfill	PV panels are assumed to be disposed of in an open dump located around 50 km from the waste generation sites.			Ecoinvent

It is clear from the survey that respondents prioritize economic impacts more than environmental impacts followed by social impacts. The low standard deviation values indicate the minimum spread of values for a given criterion among the survey participants. These assessment criteria are quantified through LCA and stakeholder engagement for the various waste management strategies detailed in this section. The weights assigned to the assessment criteria are then considered along with quantitative values for each waste management strategy and a final ranking is done using the DECERNS software. It should be noted that a similar analysis was carried out for the sustainable management of fishing net waste in Norway, but nevertheless, this study is the first of its kind for photovoltaic modules [36].

3.2. *Multi-attribute value theory (MAVT) analysis*

The multi-criteria decision analysis (MCDA) model for proposed evaluation of EoL management alternatives for c-Si PV panels is shown in Fig. 6.

3.2.1. *Environmental assessment criteria*

The environmental assessment criteria were calculated against the various EoL management alternatives through the LCA process. The bulk recycling process was assumed to be from a pilot plant in India, whereas the high value recycling process was modelled based on the FRELP project [11]. For the landfill of PV panels alone, values were chosen from the literature [37].

3.2.2. *Economic assessment criteria*

The processing costs for the FRELP process were taken from Markert et al. [38] by adding the consumable cost, electricity cost, and process waste disposal cost. For landfilling, the processing cost for disposal is reported as $32/ton [37]. For the bulk recycling process, the processing cost for both the centralized and decentralized scenario is reported as $168/ton [12].

The transport cost was calculated based on t.km (tonnes km) required for waste collection, disposal, and downstream vendor supply. The transport cost of Rs. 2.58/ton.km (0.03 €/ton.km) was taken in the Indian context based on a report by NITI Aayog [39]. FRELP required transportation of 467.13 ton.km, whereas landfill, decentralized, and centralized scenarios required 50, 369, and 453

Table 4
Weights of sustainability dimensions and assessment criteria derived from the survey.

Assessment Criteria	Mean	Standard Deviation	Weight
Sustainability Dimensions			
Environmental	0.36	0.16	0.35
Economic	0.41	0.13	0.4
Social	0.25	0.18	0.25
Assessment Criteria			
Environmental Impact			
Greenhouse Gas Emissions	0.3	0.14	0.2
Cumulative Energy Demand	0.3	0.13	0.2
Material (Human) Toxicity	0.38	0.12	0.25
Metal Depletion	0.32	0.14	0.21
Eutrophication Potential	0.22	0.13	0.15
Economic Impact			
Processing costs	0.37	0.09	0.22
Transport cost	0.33	0.12	0.19
Readiness of Technology	0.34	0.11	0.2
Revenue Generation	0.37	0.11	0.22
Technology Transfer cost	0.29	0.12	0.17
Social Impact			
Consumer awareness and public participation	0.34	0.11	0.22
Job creation	0.30	0.10	0.20
Eco-industrial partnership	0.33	0.10	0.22
Formalizing of informal sectors	0.27	0.13	0.18
Upskilling of workers	0.29	0.13	0.19

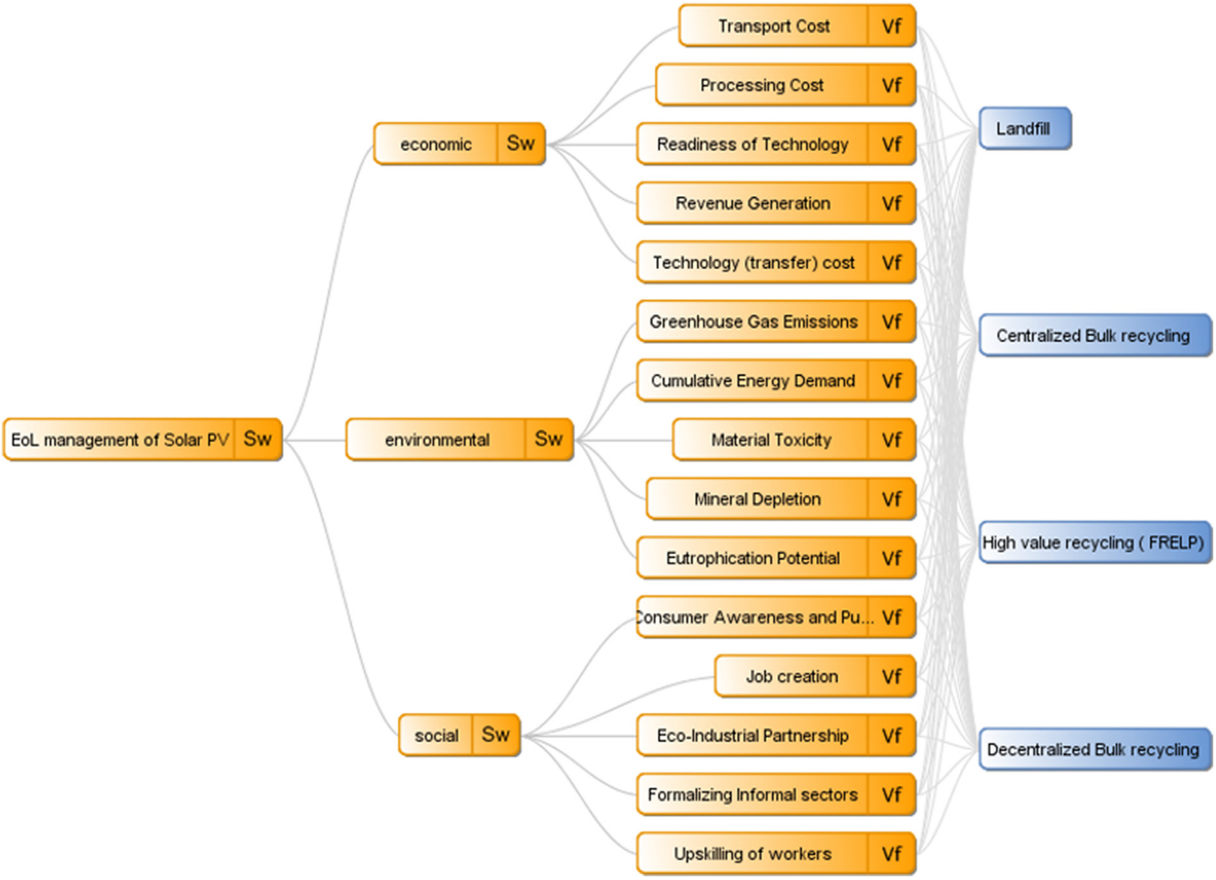

Fig. 6. MCDA model for EoL management of PV panels using DECERNS.

ton.km, respectively [11].

The revenue generated by the EoL management alternatives was retrieved from the literature [37] based on the materials recovered. Technology readiness level (TRL) was assumed for a scale of 1–9 from basic principles observed to an actual system proven in an operational environment. FRELP can be rated a TRL of 7, as the system prototype has been successfully validated in a similar operational environment. In contrast, TRL 8 is given for mobile recycling services (decentralized), as they are already available as a complete system [40,41]. Landfill and bulk recycling are rated at TRL 9, as they are commercially available and operated. Technology (transfer) cost refers to the effort involved in disseminating a technology from a start-up or pilot stage to a commercial stage. As no quantification of those costs was available in the literature, a ranking system (1 - low cost needed, 0.5 - medium, 0.25 - high, 0 - very high cost needed for technology transfer) was considered.

3.2.3. *Social assessment criteria*

The estimated full job employment per 10 000 tonnes of waste is 9.2 for bulk waste recycling and 2.8 for landfill disposal. For FRELP and decentralized recycling, the number of jobs of bulk waste recycling was multiplied by a factor of 2 and 1.5, respectively [42]. This is done after considering the number of process steps involved and the complexity of the activities. For the rest of the social assessment criteria, a ranking system (1 - high, 0.5 - medium, 0.25 - low, 0 - very low or not possible) was adopted based on expert interviews and stakeholder consultation.

The performance of the alternatives against the assessment criteria is presented in Table 5.

The performance of EoL alternatives against the various sustainability indicators are along expected trends. The bulk recycling technologies have lower environmental benefits compared to the high value material recycling technology. The landfill of PV panels have a significant environmental impact, which is indicated by the positive value. Among the bulk recycling technologies, the decentralized method of recycling, has slightly higher environmental benefits compared to the centralized systems due to its lower transportation demands. The environmental results are in agreement with those reported in the existing LCA studies on c-Si PV waste management [29].

3.2.4. *Ranking*

For ranking the waste management strategies, a linear additive function is adopted, which aggregates the weights in Table 4 and different criteria scores in Table 5.

Considering only the environmental sustainability indicators, high value material recycling processes (close to 100% material recovery) is the most preferred option followed by decentralized bulk recycling. This can be attributed to the fact that high value material recycling recovers close to 100% materials in the waste c-Si PV panels, thereby re-circulating the material instead of disposal to the environment. The decentralized material recycling, which is the second most preferred, reduces transportation related environmental impacts due to its onsite recovery of materials from waste c-Si PV panels. Landfilling of c-Si PV panels remains the least preferred environmentally sustainable option.

Shifting the focus to only economic sustainability indicators, it becomes very interesting to note that landfilling of c-Si PV panels is

Table 5
Performance of EoL alternatives against assessment criteria.

Assessment Criteria	Unit	Centralized bulk recycling	Decentralized bulk recycling	High-Value Recycling (FRELP)	Landfilling of PV panels
Greenhouse Gas Emissions	$kgCO_2e$	−3021	−3040	−3539	82
Cumulative Energy Demand	MJ	−31871	−32173	−36354	963
Human Toxicity	kg 1.4DBeq	−3164.7	−3169.84	−4395.4	5.1
Metal Depletion	kg Fe eq	−17.83	−17.83	−18.41	2200
Eutrophication Potential	kg P eq	−1.63	−1.63	−1.93	0.002
Processing costs	Euros/ton	142.6	185.5	207.09	27.16
Transport cost	Euros	13.53	11.03	13.97	1.5
Readiness of Technology	TRL	9	8	7	9
Revenue Generation	Euros/ton	141.45	141.45	428.57	0
Technology (Transfer) cost	Ranking	1	0.5	0.25	1
Consumer awareness and public participation	Ranking	1	1	1	0
Job creation	Number	9.2	13.8	18.4	2.8
Eco-industrial partnership	Ranking	0.5	0.5	1	0
Formalizing of informal sectors	Ranking	0.5	1	0.25	0
Upskilling of workers	Ranking	0.25	0.5	1	0

the most preferred option. This is due to the high processing costs of c-Si PV recycling compared to landfilling. Therefore, a clear emphasis needs to made on a landfill ban in order to encourage and stabilize c-Si PV recycling practices while it is in its nascent stage. The second most preferred economic option is centralized bulk recycling, which recovers only the major constituents of c-Si PV panels, such as aluminium frames, glass cullets, junction boxes, and cables, while disposing the solar cell materials. This is reflective of the current situation in PV waste regulated regions like the EU where bulk centralized recycling is the widely used option. The least preferred economic option currently is the high value material recycling. This information can serve as a feedback to regulatory authorities to standardize secondary material inclusion in the production of metals, thereby improving the revenue generation of high value material recycling, and to the R&D sector to look at options to lower the processing costs.

Finally, a complete focus on only the social sustainability indicators points to a similar trend among the waste management strategies as seen in the environmental sustainability indicators scenario. High value material recycling is the most preferred due to its increased potential in job creation and possibilities for eco-industrial partnerships. This is followed by decentralized bulk recycling and centralized bulk recycling practices.

However, when combining the three sustainability indicators (environmental, economic, and social), the ranking as depicted in Fig. 7 is obtained. It can be seen that high-value recycling using FRELP is the preferred process, closely followed by centralized recycling and decentralized recycling. The difference between the centralized and decentralized process lies only in the alteration of the transportation route. In the decentralized recycling scenario, it is assumed that the junction box and aluminium frame are removed in the waste generation site (e.g., PV power plants) and sent for downstream processing in the 50 km vicinity of the site, while the remaining PV sheets are stacked and sent to the centralized recycling facility. Although decentralized recycling has an advantage over the centralized recycling scenario in the environmental impact categories and transport costs, the stakeholder prioritization of the sustainability criteria influences its ranking. Landfilling of c-Si PV panels is the least preferred option, which has already been reported in literature [26].

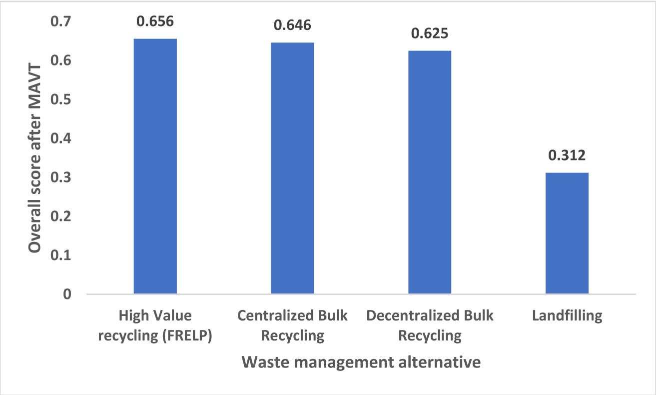

Fig. 7. Ranking of Alternatives for EoL management of Solar panels.

3.3. Sensitivity analysis

Sensitivity analysis based on the changes in the weightage of economic, environmental, and social impact criteria and the corresponding most preferred alternative was performed and is detailed in Fig. 8.

The sensitivity analysis was performed by varying the weight of the selected impact category whilst adapting the rest of the category based on the original scores. By changing the weight of the economic criteria, it is clear that the ranking is not robust. The tipping point of high-value recycling as the most preferred option is at a weight of 0.42, which is near the current value of 0.4. It can be concluded that high-value recycling becomes the most preferred option when economic weight is assigned to be less than 0.4. In contrast, centralized recycling becomes the preferred option between 0.42 and 0.74, after which landfilling of PV panels becomes the most preferred option.

For the environmental criteria, although high-value recycling continues to be the most preferred option from 0.35 until 1, below 0.3, the most preferred option changes to centralized recycling. Therefore, with respect to the environmental criteria, the presented model is more robust.

A similar scenario applies to the social criteria, with high-value recycling remaining as the preferred option from 0.2 until 1, below which centralized recycling takes over.

The sensitivity analysis clearly suggests that anticipatory life cycle analysis is only reflective of the effectiveness of the stakeholder engagement. It must be noted that because it is a subjective exercise, the identification and participation of relevant

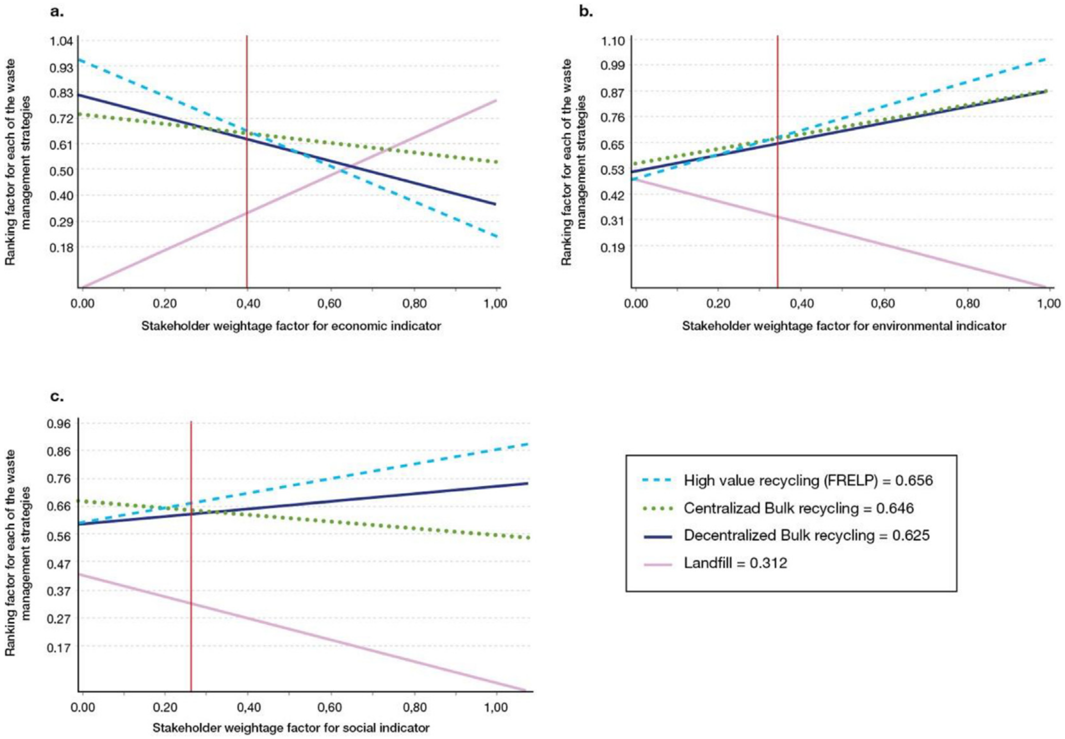

Fig. 8. Sensitivity Analysis based on changes in Economic, Environmental, and Social impact criteria (Red vertical line indicating the overall weightage of the selected criteria).

stakeholders around the topic are necessary for robust results. In addition, it also highlights the complexity of this methodology that approaches the integrated sustainability analysis and the need to evaluate the best strategy for the EoL management of c-Si PV solar panels at both the national and local level. Moreover, it also indicates that the business as usual model is obsolete in dealing with this type of waste and circular economy schemes should be integrated in order to guarantee that PV technology will be one of the main actors in the energy transition.

4. Conclusion

The research has formulated an a-LCA framework for EoL management of c-Si PV panels. With the stakeholder engagement performed in this research, high value material recycling or 100% material recovery seems to the most sustainable option for EoL management. The results from this a-LCA analysis can be used to provide feedback to recyclers, technology developers, and research funders to re-orient R&D strategies and to sustainably develop EoL management of c-Si PV panels.

Considering the improvement feedbacks attained from this research, high value recycling process developers need to work on lowering the processing costs for their technology either through scaling up or through economic incentives/regulatory instruments. Bulk material recycling needs to lower their environmental impact. This can be achieved by lowering transportation impacts through mobile recycling devices or by improving the material recovery rates through process R&D. It is very clear from this analysis that landfilling of c-Si PV panels is still the most preferred waste management strategy while considering only the economic factors. This emphasizes the need to curtail landfilling through regulatory restrictions or to increase the landfilling fees so as to avoid this disposal practice.

The important limitation for the a-LCA model is its overreliance on stakeholder engagement. The subjectiveness of the stakeholder preferences in the survey was reflected in the delicate nature of the model. Therefore, relevant stakeholder selection and engagement are of prime importance in order to establish the robustness of the model results.

The advantages of the a-LCA model are its replicability and iterative ability for various combinations of waste management strategies. This research work can be expanded to include other waste management alternatives, such as chemical and thermal delamination methods, incineration, energy recovery, reuse, refurbishment, and can be applied to other emerging PV technologies, such as perovskites, with different sets of sustainability indicators.

Credit author statement

Kishore Ganesan: Conceptualization, Methodology, Software, Writing; Dr. César Valderrama: Review, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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