ORIGINAL PAPER

End-of-life solar photovoltaic panel waste management in India: forecasting and environmental impact assessment

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Abstract

Presently, India is in the stage of installation of solar photovoltaic panels and no focus is being given towards the impending problem of handling solar waste. The absence of adequate regulations, guidelines and operational infrastructure for photovoltaic waste in the country may lead to waste being inappropriately landfilled or incinerated in a manner that may be detrimental to human health and the environment. Business as usual projection estimates 6.64 million tonnes and 5.48 million tonnes of waste generation due to the early and regular losses using the Weibull distribution function, respectively by 2040 in India. The current study also systematically investigates various policies and legislation developments on the end-of-life of photovoltaic modules in various regions of the world, to identify gaps for further assessment. Using life cycle assessment methodology, this paper compares the environmental impacts of landfilling end-of-life crystalline silicon panels with avoided burden approach due to the recycling of materials. It has been demonstrated that solar photovoltaic recycling and reusing the recovered materials will result in impact reduction in the forthcoming production phase by as high as 70%. Further, the outcomes of carbon footprint, single score indicator with the application of Intergovernmental Panel on Climate Change also predicts lower values for avoided burden approach due to recycling (15,393.96 kgCO$_2$ eq) in comparison to landfill approach (19,844.054 kg CO$_2$ eq). The outcomes of this study aim to illuminate the importance of the sustainable management of photovoltaic panels at end-of-life.

Introduction

With the advent of new technologies and products in markets, older products are rapidly becoming obsolete. The volume of waste, particularly, e-waste is growing rapidly. A developing country like India has become a dumping ground, because of waste accumulation not only from waste generated within the country but also from waste being dumped illegally from developed countries (Arya and Kumar 2020; Kumar and Dixit 2018, pp. 36–52). On one hand, India is still grappling with challenges to find solutions for the e-waste problem and on another hand, with growth and rapid advancement in the deployment of solar energy resources in the country, the chances of solar waste turning into a bigger environmental problem are looming large (Chaudhary and Vrat 2018, pp. 5–14; Prabhu et al 2022, pp. 507–534; BTI, 2019). World over, the major thrust is on the improvement of production efficiency, and very little or no attention is paid to the slowly but surely increasing the photovoltaic (PV) waste problem. The PV effect involves the conversion of light (photons) into electricity. The complete system of energy generation from the PV system can be divided into two parts viz. the balance of system (BOS) and PV modules. BOS is a collection of devices that includes an inverter, transformer, wiring, mounting and tracking systems, charge regulators, sun trackers, and batteries. Several studies on PV waste assessment conducted the world over have excluded the BOS wastes and focussed only on the wastes generated from the PV module or panel (Dias et al 2016, pp. 220–225; Xu et al 2018, pp. 450–458; Yi et al 2014, pp. 797–807). Solar PV panels can be broadly classified into three generations: (1) crystalline silicon (c–Si)

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wafer based (monocrystalline or polycrystalline); (2) thin-film (amorphous silicon, cadmium telluride, copper indium gallium selenide—CIGS); and (3) concentrator photovoltaic and emerging technologies (CPV solar panels, dye-sensitized solar panels, organic solar panels, and hybrid panels). Out of these different types of PV panel modules, the most prevalent module types are wafer-based (monocrystalline and polycrystalline) and thin-film. Wafer based silicon panels in comparison to thin film solar panels have higher conversion efficiency and are the most widely used solar panels commercially. Wafer-based PV technology accounted for nearly 95% of the total production in the year 2019 (FISES, 2020). The modelling in the current study is done based on the rate of installation of crystalline technology since it is anticipated that crystalline Si-wafer-based technology will dominate the solar PV panels market share in the next decades. From the perspective of PV waste determination, the complete life cycle of a solar PV module can be divided into the following stages

a. Processing and production stage

In comparison to polycrystalline panels, the making of monocrystalline panels results in production of more waste since they are made from silicon ingot slices—leaving off-cuts, etc. However, this waste can be further utilized to make polycrystalline or multi-crystalline PV modules. In thin-film silicon panels there is a reduction in the volume of material needed as they are made by spraying a thin layer of silicon onto the surface, so has the potential to reduce impacts and waste. Production waste is the most easily managed waste as manufacturers are well equipped to handle such waste and production waste is not a societal waste management problem (IEA, 2016).

b. Transportation stage

Panels may get damaged due to their transportation from the manufacturing to the installation site. The major reason is the ill-handling of PV modules during the loading and unloading of PV panels.

c. Operation stage

Faulty installation practices along with extreme weather conditions like hailstorms, floods, cyclones, etc. may also result in the generation of solar waste during the initial and active life cycle of solar panels.

d. End-of-life stage

PV modules reach their end-of-life (EoL) stage when the overall power output of modules drops below 80% of the initial quoted value at the time of manufacture (CERC 2011). This stage will contribute to maximum waste generation typically after the actual life cycle of 25–30 years of the solar PV module (CERC 2017; Domínguez and Geyer 2017, pp. 29–41; IEA, 2016; Lugo-Laguna et al. 2021, pp. 3238; Mahmoudi et al. 2019, pp. 192–205; Paiano 2015, pp. 99–112). The exponential growth in the installation of PV capacity in recent years means there will also be a rapid increase in the number of panels reaching their EoL stage (Shin et al 2017, pp. 1–6).

Figure 1 shows various stages of solar PV waste generation during the complete life cycle of the solar PV module. The cycle shown in the continuous line is an open cycle, however, if dotted lines are incorporated, the use of raw materials is not only minimized but also burdens on the environment are also minimal. Currently, in absence of any significant waste recycling techniques, there is a high dependency on the supply of raw materials from natural resources during the production stage.

European countries played a key pioneering role during the early developments of PV. Asia's share started to grow rapidly in 2012 and it has not abated since then. Asia represented around 57% of the total cumulative installed solar PV capacity in 2019 primarily driven by China, India, Japan, Korea, and others. During 2019, around 115 GW of PV systems have been installed and commissioned in the world leading to a total cumulative installed capacity of 627 GW. Despite the shrinkage of the Chinese PV market for the second year in a row from 53.0 GW in 2017 to 43.4 GW in 2018 and 30.1 GW in 2019, China remained the leader in terms of total capacity with almost one-third of the global PV installed capacity. During 2019, India's annual market reached 9.9 GW which also includes around 1.1 GW of distributed and off-grid installations. In the top 10 countries, there are China, India, Japan, Vietnam, Australia, and Korea representing Asia–Pacific countries, three European countries namely Spain, Germany, and Ukraine, and one country in the Americas i.e., the USA (IEA, 2020).

In this paper, an attempt for estimation of solar PV waste in India by 2040 has been made using the Weibull distribution function. The study also explores the prospects of the circular economy by comparison of the environmental impacts of landfilling with avoided burden approach due to the recycling of materials that will result in substituting virgin raw materials with recycled materials in the forthcoming production stage. The paper is organised as follows: first, an analysis of the literature survey reviewed and motivation for the study, followed by a discussion on the overall methodology adopted for performing solar PV waste estimation is carried out. Next, the national and international scenarios for solar PV waste management and proposed solar PV waste reduction strategies for India are discussed. Lastly, the life cycle assessment using SimaPro software is carried out. This
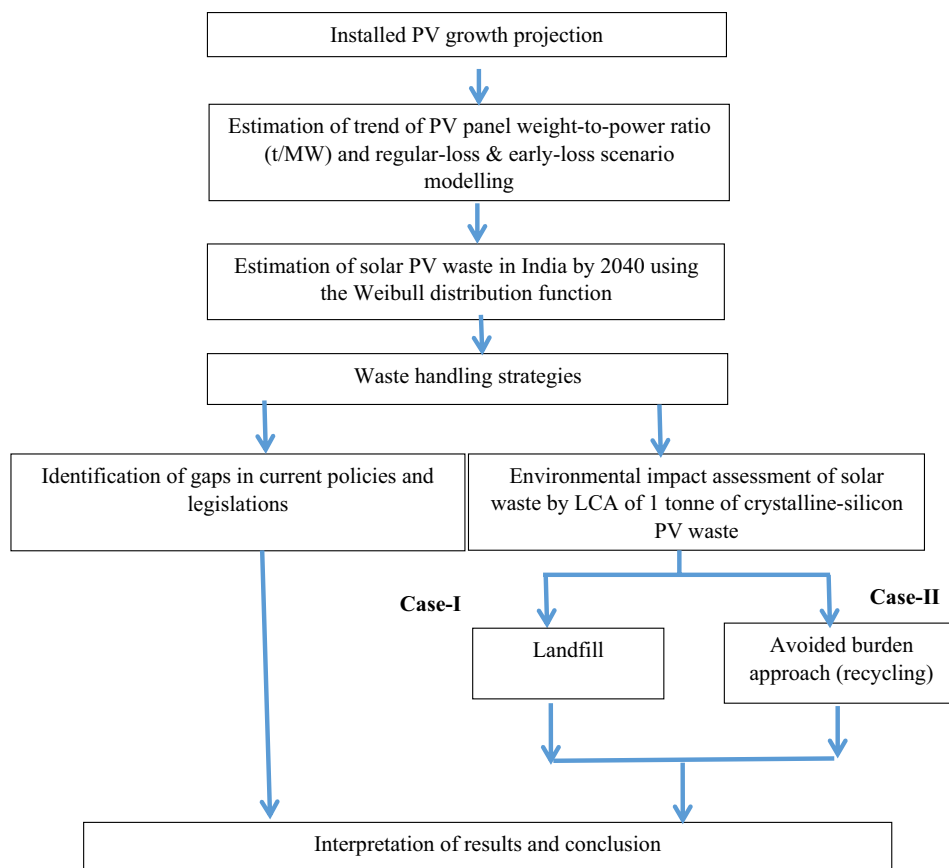
Fig. 1 Various stages of solar PV waste generation
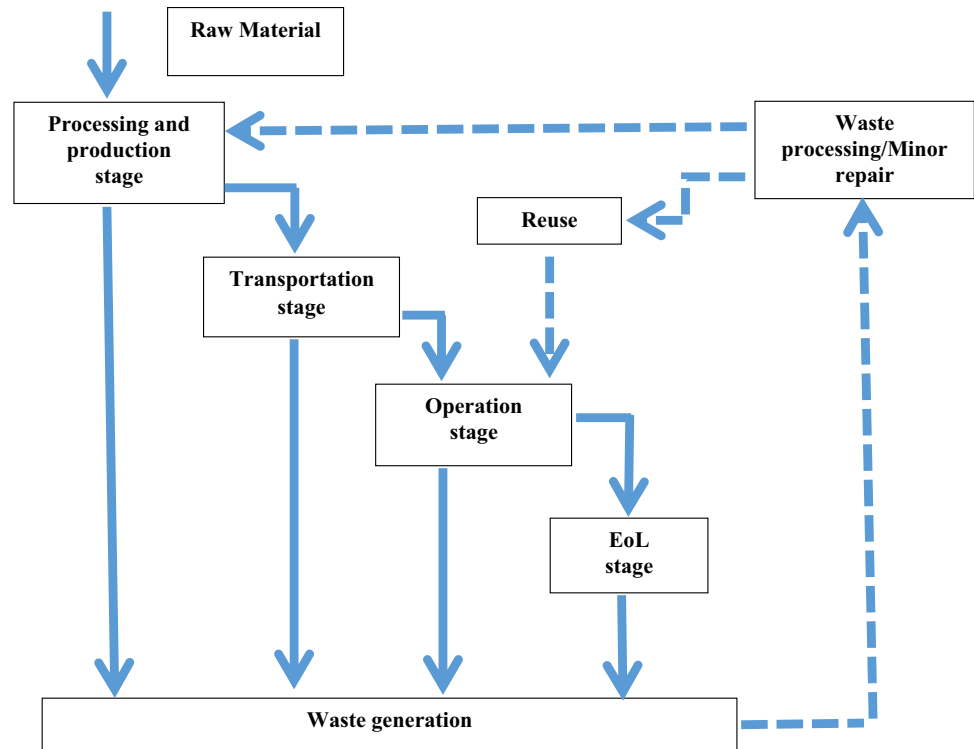
is followed by a discussion on the overall life cycle impact comparison amongst different PV waste disposal methods and the conclusion of the study along with recommendations for future work. Finally, Appendix (Tables 4, 5, 6 and 7) is included at the end of the text, the first one showing tonnes per megawatt (t/MW) variation of Waaree solar panels, the second one showing the list of various uncertainties encountered throughout the conduct of the present study, the third one giving list of background input datasets used in life cycle inventory analysis and the last one giving the amount of recovered materials.

Different studies conducted in different regions across the world have estimated different values of accumulation of solar waste. Domínguez and Geyer (2017, pp. 29–41) estimated that in Mexico for each GW of installed PV capacity, around 4 million PV modules waste will be generated by 2045, and PV modules will constitute 691 thousand metric tonnes of PV waste. In another study done for the USA by the same authors (Domínguez and Geyer 2018, pp. 1188–1200), it is estimated between 2030 and 2060, a total of 9.8 million metric tons of PV waste will be generated that includes 6.6 million metric tons of PV modules waste, 2.7 million metric tons BOS waste, 0.3 million metric tons inverters waste, and 0.215 million metric tons transformers waste. Paiano (2015, pp. 99–112) projected the PV crystalline silicon waste amount in Italy for two periods i.e., between 2012–2038 and 2039–2050 based on the 25 years lifetime of PV panels. The estimated amount during 2012–2038 is 1,957,099 tonnes, corresponding to the photovoltaic installations from 1987 to 2013, and the amount during

the period 2039–2050 as 6,281,868 tonnes, corresponding to the installations during 2014–2025. Peeters et al (2017, pp. 14–26) highlighted the uncertainty in estimating the PV waste volumes owing to the rapid development of PV technology. The authors estimated the amount and material composition of waste from silicon-based PV modules based on the theory of the bathtub curve in Flanders, Belgium. Faircloth et al (2019, pp. 260–272) estimated that in Thailand, 5000 t of PV waste will have accumulated by 2025 and by 2030, the country will be producing at least 8000 t of PV waste per year. Similarly, actual PV installation in Australia from 2001 to 2018 formed the basis for the fact that 0.8 million tonnes of cumulative PV waste will be generated by the year 2047 based on the study by Mahmoudi et al. (2019, pp. 192–205). Corcelli et al (2018, pp. 37–51) used SimaPro 8.0.4.30 and ReCiPe midpoint impact assessment method to compare two treatment scenarios that include high and low recovery rates in a laboratory scale and highlighted that the recycling of the PV panels generates large environmental benefits at the material recovery level as well as the scale of the biosphere (pollution prevention). A pilot-scale project named full recovery end-of-life photovoltaic (FRELP) for the treatment of the EoL crystalline PV modules was studied by Latunussa et al (2016b) for conducting the environmental impact assessment of the EoL PV panels based on the industry data. This study excludes the analysis of the production of secondary raw materials. For India, Pankadan et al (2021, pp. 1361–1371) predicted 0.4 million tonnes and 0.038 million tonnes of waste due to early and regular losses

Fig. 2 Description of paper methodology

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┌─────────────────────────────────────────┐
│         Installed PV growth projection    │
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                    ↓
┌─────────────────────────────────────────┐
│  Estimation of trend of PV panel weight- │
│  to-power ratio (t/MW) and regular-loss  │
│      & early-loss scenario modelling      │
└─────────────────────────────────────────┘
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┌─────────────────────────────────────────┐
│  Estimation of solar PV waste in India   │
│  by 2040 using the Weibull distribution  │
│                function                    │
└─────────────────────────────────────────┘
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┌─────────────────────────────────────────┐
│          Waste handling strategies         │
└─────────────────────────────────────────┘
          ↓                         ↓
┌────────────────────┐   ┌──────────────────────┐
│ Identification of  │   │ Environmental impact │
│ gaps in current    │   │ assessment of solar  │
│ policies and       │   │ waste by LCA of 1    │
│ legislations       │   │ tonne of crystalline-│
│                    │   │ silicon PV waste     │
└────────────────────┘   └──────────────────────┘
        │              Case-I ↓          ↓ Case-II
        │            ┌──────────┐  ┌──────────────┐
        │            │ Landfill │  │ Avoided burden│
        │            │          │  │ approach      │
        │            │          │  │ (recycling)   │
        │            └──────────┘  └──────────────┘
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│     Interpretation of results and conclusion    │
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respectively by 2030, and 7.99 million tonnes and 3.61 million tonnes, due to early and regular losses respectively by 2050.

It is revealed from the literature review that most of the studies are concentrated particularly towards solar PV waste estimation, life cycle, and economic assessment of PV panels, but still, there are considerable gaps in these studies, as the success of the EoL solution of solar PV panels depends on the robustness of local regulatory and policy framework and overall participation of various stakeholders viz. original equipment manufacturers, solar PV system installers, consumers, recyclers, and various government organizations. None of these studies conducted so far has highlighted the enormity of the impending solar PV waste problem in India. In comparison to the available scattered literature on solar PV waste estimation in India, the present study also highlights the effect of the COVID-19 pandemic on waste volumes. Presently, solar PV module and battery waste are considered general electronic waste and its effective and safe disposal come under the Ministry of Environment, Forest and Climate Change (MoEFCC), and even despite the presence of the e-waste regulation in place since 2011, only 5% of the estimated e-waste is recycled in the organized or formal sector (Turaga et al 2019, pp. 127–162). India is undergoing a clean energy transition. The government is implementing various programmes and regulatory measures into place to raise the percentage of renewable energy sources in the overall mix of electricity. Among different renewable energy sources, significant capacity addition in solar energy in the form of rooftop and utility-scale solar installation has been made. Solar power from an energy requirement point of view promises a bright future for India, but behind the gleam is a growing mountain of e-waste. With the current growth rate of solar PV, the solar waste problem will turn into a serious environmental problem in the next decades unless addressed at this stage. The country lacks even conventional recycling facilities to separate glass and aluminium frames from the modules.

To this end, the present study is undertaken to estimate the volume of solar PV waste in India, particularly at the time when the country is undergoing a massive solar capacity expansion programme and also presents an environmentally benign strategy to policymakers for the handling of solar waste using life cycle assessment (LCA) methodology. The role of avoided burden approach due to recycling of materials from the point of view of circular economy prospects has been discussed. Additionally, the breakups of the amount of materials that can be recovered along with environmental gains associated with their replacement from virgin material are also discussed.

Materials and methods

PV panel waste volume will increase along with the PV deployment rate. One of the easiest ways to predict waste streams is by considering a fixed loss scenario. This scenario assumes that after the lifetime of the PV panel (25–30 years) it will be discarded. On the other hand, the cumulative PV waste generation can be obtained more accurately for regular-loss and early-loss scenarios by the multiplication of the probability distribution function with the weight of panels installed in a particular year. In this paper, the methodology as shown in Fig. 2 has been adopted. Despite every effort that has been made in the present study to predict the solar waste data and its effect on the environment with accuracy, various assumptions have been taken throughout the study that may affect the outcomes. The probable sources of some of the uncertainties are given in the Appendix (Table 5).

Solar PV waste estimation

Without waiting for the end of life of solar cells which typically varies from 25 to 30 years the slowly and surely increasing problem of solar waste can be best addressed by estimating solar waste using a mathematical probability distribution function based on its projected growth. In India, significant solar PV installation started near the year 2010, the corresponding PV waste due to regular loss scenario should be generated by 2035–2040 (RS 2021b) and it can be said that the critical point from a waste generation point of view, will reach by 2040. To estimate the solar PV waste in India firstly, futuristic PV installed capacity is projected under two scenarios i.e., the business as usual (BAU) scenario and the ambitious scenario. Secondly, tonnes/MW projection to estimate the weight of waste generated is carried out. Finally, mathematical modelling using Weibull distribution is carried out to predict waste volumes.

Installed PV growth projection

In India, the cumulative capacity of solar PV installation as on 31.03.2022 is 53997 MW and that constitutes a share of 13.5% in overall installed capacity compared to 10 MW in 2010 (MoP 2022; NITI 2021).

The government of India is committed to achieving an already set target of 100 GW of solar energy by 2022 (RS 2021a). With the BAU scenario, cumulative solar installed capacity will reach around 339 GW by 2040. The genesis of the ambitious scenario is the numbers provided by NITI Aayog given under the draft national energy policy (NITI 2017). The anticipated cumulative capacity at the end of 2040 will be 395 GW. The anticipated maximum solar capacity of India is 750 GW (PIB 2020), therefore even if the ambitious scenario is considered; only approximately 50% of the maximum solar capacity of India will be achieved by 2040. These anticipated projections will form the basis for the estimation of solar PV waste.

Tonnes/MW estimation

Waste estimation depends on the weight of the panel being used for installation. The advancement of technology has resulted in thinner frames, glass layers, and wafers along with improved efficiencies thereby resulting in lighter solar panels in other words given the same weight of the panel, more wattage can be accommodated now. The factor t/MW or kg per watt depends on the type of solar technology, size & weight of the panel, solar cell efficiency, and other characteristics of the panels. Earlier studies across the world have taken this factor in the range of 90–100 t/MW (HBR 2021; Sander et al 2007). However, in the present study, no constant factor for t/MW has been taken rather its value has been extrapolated, and thus values are more reflective of the expected future weights of installed solar PV panels. The major challenge encountered in obtaining this information from ecoinvent or from the datasheet of solar modules is the lack of availability of data pertaining to the weight of the PV model vis-a-vis its manufacturing year. Therefore, in the present study, the information pertaining to the yearly variation of t/MW of one of the major solar PV manufacturer companies in India i.e., Waaree renewable technologies ltd. has been obtained via correspondence through email Appendix (Table 4).

The obtained data have been fitted appropriately to an exponentially decreasing function given by Eq. 1.

$$\text{Mass to power ratio} \left(\frac{t}{MW}\right) for\ i^{th}\ \text{year} = A \cdot e^{-i/B} \quad (1)$$

where, $A = 89.416$ t/MW, B (exponential time constant) $= 37.037$ and the value R^2 corresponding to the

Table 1 Values of the average lifetime of solar panels reported in various studies

Region	Global (IEA, 2016)	Europe (Lugo-Laguna et al. 2021, p. 3238)	Italy (Paiano 2015, pp. 99–112)	Mexico (Domínguez and Geyer 2017, pp. 29–41)	Australia (Mahmoudi et al. 2019, pp. 192–205)	India (Present study)
Average lifetime (year)	30	25	25	30	30	25

Fig. 3 Estimation of PV panel waste using early and regular loss scenarios for India
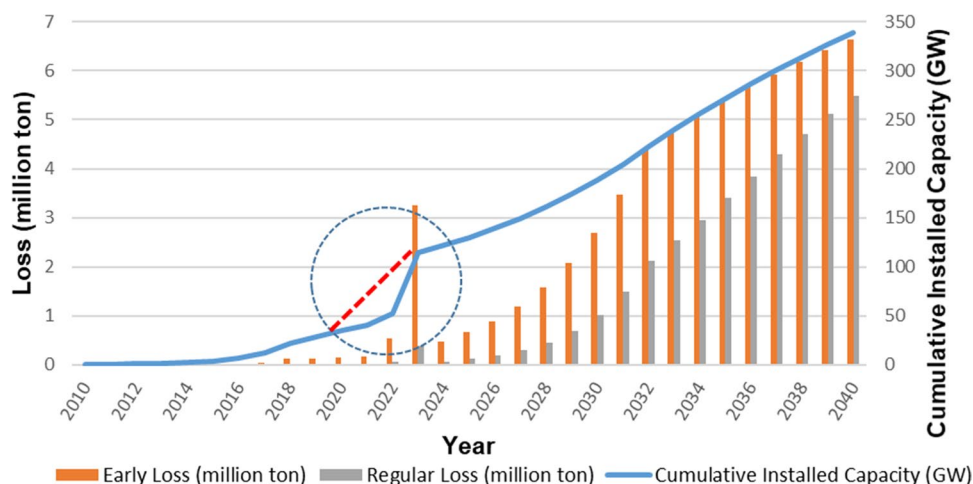
coefficient of determination of fitting has been taken as 0.9691.

Mathematical modelling using Weibull distribution

Solar module failures like a failure in other equipment, sub-system, or components follow the "bathtub" curve i.e., most common failures occur near the beginning and near the end of the component's lifetime. The three main PV panel failure phases are 1. Infant mortality failure, 2. Midlife failure, and 3. Wear-out failure (IEA, 2014).

Infant mortality occurs at the commencement of the working life cycle, and midlife failures of PV occur from five to eleven years after installation. Further, wear-out failures like delamination, occur from after 12 years of installation to 25–30 years i.e., at the end of the lifetime of PV modules (IEA, 2016).

The anticipated lifetime of PV modules spans several decades in the range of 25–30 years. Device lifespan is the amount of time a device operates as intended, in accordance with design standards, and under predetermined circumstances, before failing. Device life expectancy typically follows a probability distribution. The materials used for manufacturing solar PV cells and design are continually changing to reduce the levelised cost of energy (LCOE) (Sharma et al 2021, pp. 126–147) and the researchers cannot wait for the end of the anticipated life of 25–30 years to identify the failure modes and mechanisms. In the present study for carrying out failure and reliability analysis of solar modules, Weibull statistics have been utilized. Weibull statistics is one of the most widely used lifetime distributions in reliability engineering and is used to assess product reliability, analyse life data, and model failure time. Weibull models can include up to three parameters: shape (α), lifespan or scale (δ), and failure-free life or location (θ). In a two-parametric Weibull model, the location parameter (θ) is set to 0.

The probability density function can be written as: (Kumar and Sarkar 2013, pp. 129–134)

$$f(x) = \frac{\alpha}{\delta}\left(\frac{x-\theta}{\delta}\right)^{\alpha-1} e^{-\frac{(x-\theta)\alpha}{\delta}} \tag{2}$$

The Weibull function for reliability can be deduced from Eq. 2 and is given by Eq. 3 as:

$$R(x) = e^{-\frac{(x-\theta)\alpha}{\delta}} \tag{3}$$

The Weibull failure rate function i.e. $\lambda(x)$ is the ratio $f(x)$ to $R(x)$ and is given as

$$\lambda(x) = \frac{f(x)}{R(x)} = \frac{\alpha}{\delta}\left(\frac{x-\theta}{\delta}\right)^{\alpha-1} \tag{4}$$

Thus, to estimate the failure rate over time, the parameters α and δ need to be determined.

The above Weibull cumulative distribution function can be transformed into a straight-line equation form i.e., $Y = mX + b$: (Kumar and Sarkar 2013) as given in Eq. 5

$$F(t) = 1 - e^{-\left(\frac{t}{T}\right)^{\alpha}} \tag{5}$$

where, t = time in years and T = average lifetime. The shape parameter α controls the typical S shape of the Weibull curve and describes how the failure rate changes over time. If, $\alpha < 1$, the failure rate decreases with time and is commonly associated with infantile failures or early life failures. If $\alpha = 1$ means the failure rate is constant. If $\alpha > 1$ means the failure rate increases with time and is associated with failures related to mechanical wear-out failures. Different studies the world over have taken different values of the average lifetime of solar panels varying between 25 and 30 years. An overview of the value of the average lifetime reported in various studies is given in Table 1. The average lifetime of 25 years is taken in the present study based on the Ministry of New and Renewable Energy (MNRE) regulation (CERC 2017).

The shape factor α determines the probability of regular-loss and early-loss scenarios during the panel life cycle. The present study uses 2.4928 and 5.3759 as the values of shape factors (α) for early-loss and regular-loss scenarios respectively (IEA-PVPS 2014a; IEA-PVPS 2014b; SunPower Corp, 2011).

PV panel waste projections: analysis and comparison with other studies

The COVID-19 outbreak affected the solar industry sector at a time when the country's solar project execution was at its peak. India has ambitious targets of achieving 100GW solar energy target by 2022 (RS 2021a).

Due to COVID-19, India's installed solar capacity suffered a 56% decline in the calendar year 2020 as compared to 2019 (MERCOM India 2019) mainly due to the disruption of supply chains, workforce availability, and a brake on solar equipment imports from China. The fact is evident from the dip in installed capacity during the year 2020–2021 as shown in Fig. 3. The purpose of the dotted circle in Fig. 3 is to highlight the effect of the COVID-19 pandemic on solar PV installation in India. The COVID-19 pandemic has posed tough challenges by impacting the pace of development and commissioning of renewable energy projects. Accordingly, several steps were initiated like an auction of new tenders, extensions of deadlines, advising states to maintain the sanctity of agreements, and ensuring certainty in supporting regulations for renewables to bring the sector back to the path of recovery (BTI 2020). Figure 3 also depicts an increase in installed capacity after a decline in 2020–21 due to the increased pace of implementation of projects that could not be implemented due to various COVID restrictions and lockdowns. Similar trends have also been obtained under the analysis of an ambitious scenario wherein a cumulative capacity of 395 GW will be achieved by 2040. Based on cumulative installed capacity by 2040 under BAU, the cumulative PV waste generation due to early and regular loss scenarios are 6.64 million tonnes and 5.48 million tonnes respectively and under the ambitious scenario by 2040, the cumulative PV waste generation due to early and regular loss scenario is 10.30 million tonnes and 8.51 million tonnes respectively.

India's solar waste prediction was also carried out by IEA (2016) and Pankadan et al (2021, pp. 1361–1371). IEA study predicted solar PV waste could average 50,000–320,000 tonnes by 2030, possibly ending in 4.4 to 7.5 million tonnes by 2050. Similarly, another study by Pankadan et al (2021, pp. 1361–1371) predicted 0.4 million tonnes and 0.038 million tonnes of PV waste generation due to early and regular losses, respectively for India by 2030, and 7.99 million tonnes and 3.61 million tonnes of waste generation due to early and regular losses, respectively by 2050. The main reason for the variation of waste volumes in the present study and studies

conducted earlier for India is the variation in the projection of installed capacities since the present study includes the disruptions of the solar market due to the COVID-19 pandemic otherwise the figure would have followed the dotted path (Fig. 3) and accordingly early loss figures would be quite less secondly present study assumes a 25-year lifetime for solar panels, in contrast to 30 year lifetime in IEA (2016) study and 25–30 year in the study conducted by Pankadan et al (2021, pp. 1361–1371). Thirdly present study uses power-to-weight ratio trends of an Indian solar manufacturer i.e., Waaree for the period 2015–2021 while the IEA study uses panel datasheet of leading producers of the world for the period 1980–2013 and the other study is silent on values of power-to-weight ratios.

Waste management: national and international scenario

India will likely face serious challenges regarding mechanisms to address the management of solar PV waste and its disposal in the near future as solar power waste management is a neglected sector and follows an unregularised, unscientific, and informal approach (Sheoran, Sharma and Kumar, 2020). An online PV waste monitoring system either at the early stage or EoL stage will help in assessing the flow of all discarded modules. This assessment will provide input for authorities and other stakeholders to develop regulations and policies. In a developing country like India, the model commonly found is based on a linear economy, in which different extracted raw materials are processed to make the end product, then transported to the user site, and finally discarded as waste at the EoL cycle of the product. However, in a circular economy, waste streams by different processes are converted into basic raw materials thus a continuous closed cycle will be initiated by bringing back waste to the material flow cycle. India notified the E-waste management rules, 2016 (CPCB 2018) and as compared to the E-waste (management & handling) rules, 2011, the key difference is the provision of extended producer responsibility (EPR) to ensure that electronic products are recovered for safe recycling. However, the rules are silent about solar PV waste and there is always a risk that waste PV modules end up in uncontrolled or not environmentally sound disposal operations such as uncontrolled or illegal landfills or open land (EU 2021). Lack of incentives, regulatory policies, and knowledge about the value of extractable materials and their corresponding environmental impacts are major hindrances in the safe disposal of PV waste material. Globally, it has been estimated that only 10% of the total solar PV waste is currently recycled which indicates a massive gap in the availability of the operational infrastructure (Lunardi et al 2018, pp. 9–27). With prodigious growth, the problem of solar PV waste management is inching slowly to an alarming stage in absence of a legislative and regulatory framework. Except for waste regulation for solar PV in European Union, all other

major countries lack regulation on solar PV waste disposal and relies on non-regulatory approaches to managing solar PV waste. A list of development in some major regions of the world is summarised below (IEA, 2018; Pankadan et al 2021, pp. 1361–1371; SunShot 2016).

1. *United States of America*: There is no specific federal law or regulations so presently only laws pertaining to general waste apply however, some states like California, and Washington are developing their regulation or law for PV module utilization and recycling.
2. *European Union*: First Waste electric and electronic equipment (WEEE) directive of 2003 was silent on tackling PV waste. However, modified WEEE include EoL management of PV module and as per the latest WEEE directive, PV manufacturers will have the main liability for the costs of collection, handling, and treatment of PV waste irrespective of the location of the manufacturing facility. The modified directive is applicable to all European Union members.
3. *China*: At present, there is no federal law or disposal mechanism however, PV Recycling and Safety Disposal Research programme by National High-tech R&D has provided recommendations for developing policy guidelines for addressing PV waste challenges.
4. *Japan*: The country is still in stage of developing guidelines for PV recycling. However, substantial progress is made in developing and testing technology for the recycling of PV panels.
5. *India*: In India, there is no central regulation and PV waste is treated under general waste regulations that have limited scope and apply to household electronics products only.

Strategies for India

Both the Indian government and the Indian solar industry use the E-Waste Management Rules 2016 as reference law in the absence of any rules. For example, the guidelines of Solar Energy Corporation of India Limited (SECI) for setting up grid-connected solar PV plants state that "the solar power developer will ensure that all solar PV modules from their plant after their 'end-of-life' (when they become defective/ non-operational/ non-repairable) are disposed of in accordance with the "e-waste (management and handling) rules, 2011" notified by the government and as revised and amended from time to time." (SECI 2017). Thus, there is significant scope for a regulated approach to solar waste management that will lead to environmental benefits and enhance the prospects of the circular economy by substituting virgin material manufacturing with recycled material. The following section discusses the probable waste mitigation strategies for India along with their limitations.

Reduce

The thumb rule for handling waste is first to reduce, reuse, and then recycle. Solar waste volumes can be considerably reduced by improvement in the design of products and manufacturing processes. The use of various hazardous materials like lead, cadmium, and selenium can be limited by extensive research and development. Similarly, the use of silver can be avoided due to advancements in inkjet and screen-printing technologies. New and innovative techniques in printing and pastes have been projected to reduce silver consumption from 0.16 g/Wp in 2005 to less than 0.1 g/Wp in 2020 (Perez-Santalla 2013). Efforts should be made to design a product with fewer amounts of hazardous materials. Careful handling of modules during transportation and operation stages will also result in a decrease in waste volumes.

Reuse

Both reusing and recycling strive to achieve a common goal but are different terms that are not interchangeable. Reuse is a means to prevent waste streams from entering landfills. It is the action or practice of using an item, whether for its original purpose or to fulfil a different function thus increasing the occupational well-being of citizens by taking useful products discarded by those who no longer want them and providing them to those who do. Further, recycling results in keeping waste materials out of the landfill by "collecting, segregating, processing, and manufacturing collected goods into new products" (Kralj and Markic 2008, pp. 409–418). The flaws and imperfections discovered during the early phase of a PV panel's lifecycle can be easily handled by imparting specific training and skill on PV panel repairs. In addition to extending the lifespan of PV panels, this will create a market where repaired PV panels can be sold at a lower market price than new or as used panels. A second-hand market can be developed for repaired panels and for panels that have lived up to their nominal lifetime, after necessary repairs.

Recycle

Not only solar-panel production is a highly energy-intensive process but also the presence of hazardous materials like lead, cadmium in the end-of-life panels can cause significant pollution and health issues if discharged into the environment. Therefore, the recycling of waste solar panels can reduce energy waste and environmental pollution (Cucchiella et al 2015, pp. 263–272). In the comparison of P–V and I–V characteristics of old, recycled, and new PV modules, it is observed that the characteristics of the recycled module are at par with the new module (Ashfaq et al 2017, pp. 22–28). Recycling constituent materials of solar PV

back to manufacturing will cut down imports from natural resources. There is a scope for reduction in the EoL solar PV waste in the range of 60%-90% due to the high potential of recyclability rates of the constituent solar PV materials (Domínguez and Geyer 2017, pp. 29–41; Domínguez and Geyer 2018, pp. 1188–1200; Santos and Alonso-García, 2018, pp. 1613–1628).

Based on the above discussions, dedicated PV panel recycling plants are needed to be created, even though waste recovery models are not economically viable at the present stage owing to low to moderate values of PV waste generation. The government may consider incentivizing the waste recovery units for a few initial years. The treatment of solar PV waste requires significant importance not only from environmental benefits arising from the treatment of waste but also has economic significance since the recovery of materials can be used as raw material during different stages of solar PV panels production. The solar PV waste recycling industry can be considered a secondary mining industry.

Landfill

Improper waste disposal at landfill sites as the case with e-waste disposal will result in the leaching of lead and cadmium into groundwater and will result in further worsening groundwater quality. Leaching of lead may result in reduced growth of flora and fauna, destruction of habitat, and adverse health hazards on the nervous, kidney, immune, and reproductive function systems in the human body. It may also result in

impaired brain development in children. Cadmium is a highly toxic carcinogen and is linked to lung, human prostate and renal cancer (BTI, 2019). Landfill as an option for solar waste disposal is the easiest to implement but not only it results in the loss of valuable materials but also results in economic loss and should be assigned the lowest priority while designing solar waste disposal strategies. The improper treatment of PV waste may result in the loss of potentially conventionally reusable materials like aluminium and glass which have a share of 88% in terms of weight (Latunussa et al 2016a, pp. 101–111). Not only this, but the landfill will also result in the loss of rare and/or critical metals (e.g., silicon metal) and precious metals like silver, a well-known conductor, though found in a small quantity. WEEE directive based on EPR encourages resource efficiency through reuse, recycling, and minimising the dumping of waste in landfills (Farrell et al 2020).

In April 2019, the MNRE issued a blueprint under the directions of the National Green Tribunal in Delhi, MNRE has released the concept note for the disposal, utilization, manufacturing, and import of solar PV but no progress has been made since then (MERCOM India 2019). Apart from the '3Rs' concept of sustainable waste management, i.e. reduce, reuse, and recycle, a multi-sector and multi-stakeholder coordinated approach among various ministries like MNRE, MoEFCC, Ministry of Power (MoP), SECI, solar PV manufacturers, and other stakeholders along with extended producer responsibility legislation that will cover collection, recovery, and recycling of solar PV modules is the need of the hour to tackle solar PV waste challenges.
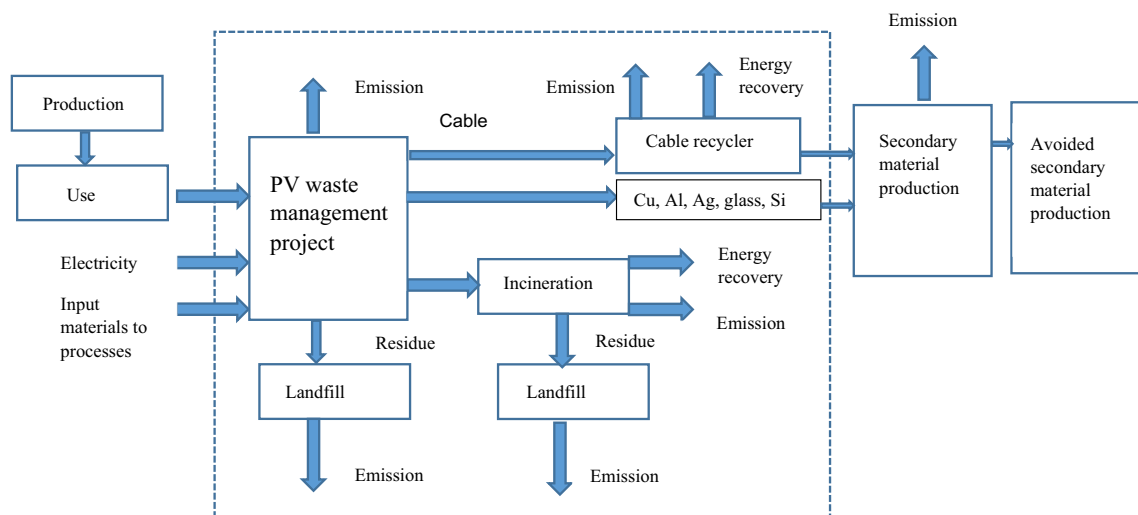

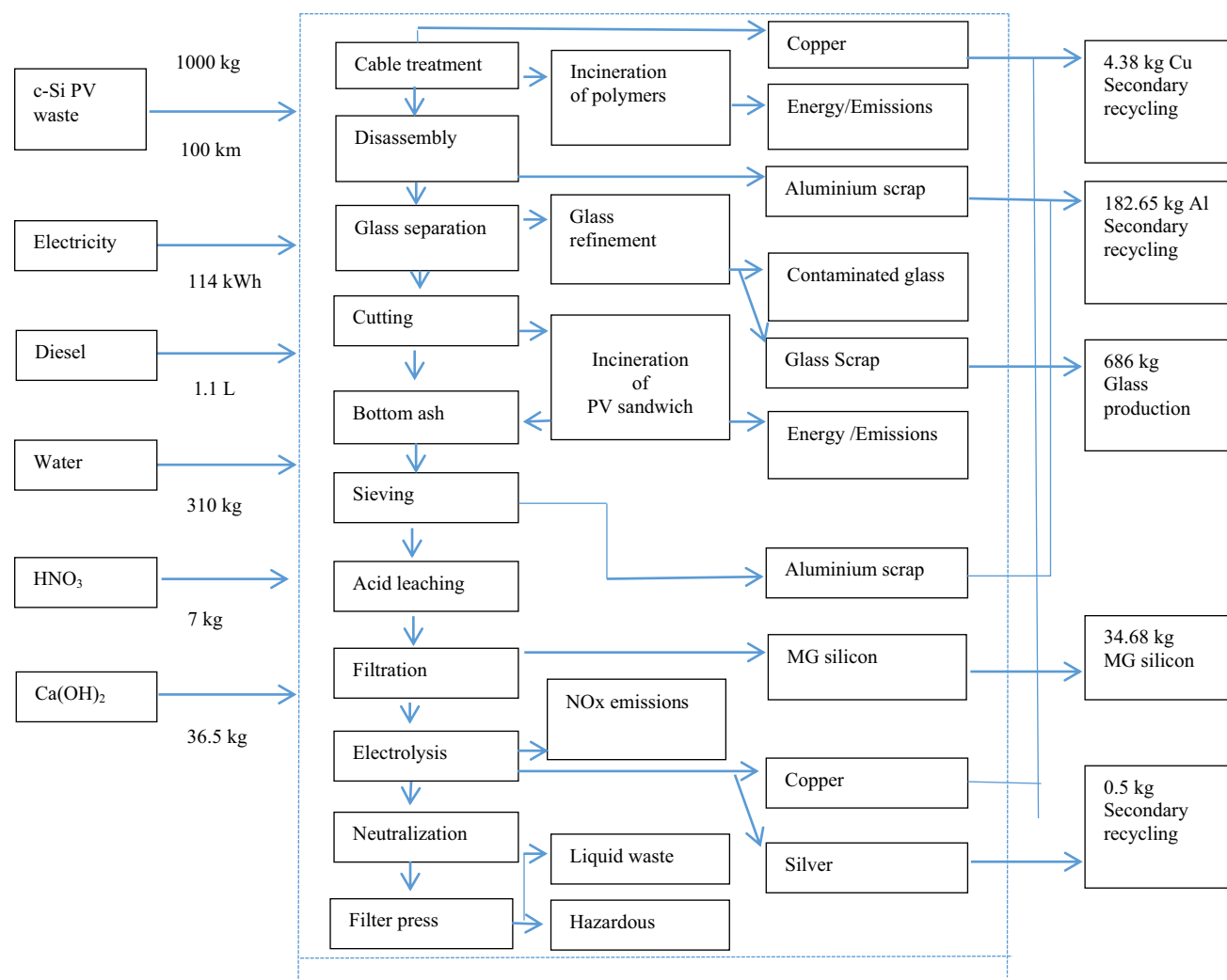**Fig. 4** System boundaries for FRELP (Latunussa et al 2016b)

Fig. 5 System diagram showing input and output stream for the FRELP recycling process (FRELP, 2015)

Life cycle assessment methodologies

The LCA is an objective procedure for assessing the energy and environmental loads related to a process or activity, carried out by identifying the energy and materials used, and the waste released into the environment (SETAC 2019). According to ISO 14040 series (ISO 2016), the analysis of LCA consists of four consecutive steps. A LCA study is initiated by defining the goals & scope, the functional unit, and the system boundary of the study in the first step. Identifying the inputs and outputs related to each stage of a product's life cycle is the next step, referred to as a life cycle inventory (LCI). In the life cycle impact assessment (LCIA) step, the evaluation of potential impacts based on the inventory is carried out.

The results of the impact assessment are analysed in final step known as the interpretation phase. The analysis of the data completeness, sensitivity, and consistency is also part of interpretation step. To carry out an LCA study, the goals and scope of the study must be explicitly stated. On basis of the inventory of energy and material, the evaluation of potential environmental impacts is assessed. The functional unit (FU) that provides a reference to which the inputs and outputs can be related must be clearly defined. The FU in the present analysis is the treatment of 1000 kg of c–Si PV waste in a recycling facility. The system boundary of an LCA should be in accordance with the stated goal of the study and it defines the unit processes to be included in the system for analysis. Presently there is no EoL recycling legislative framework in India for the

Table 2 Overall impacts of solar manufacturing process

Impact category	Unit	Solar PV manufacturing (c–Si)
Global warming	kg CO_2 eq	22,749.859
Stratospheric ozone depletion	kg CFC11 eq	0.007307048
Ionizing radiation	kBq Co-60 eq	108.91387
Ozone formation, Human health	kg NOx eq	48.103837
Fine particulate matter formation	kg PM2.5 eq	21.617138
Ozone formation, Terrestrial ecosystems	kg NOx eq	50.23211
Terrestrial acidification	kg SO_2 eq	75.725588
Freshwater eutrophication	kg P eq	2.036668
Marine eutrophication	kg N eq	0.66197535
Terrestrial ecotoxicity	kg 1,4-DCB	174,726.93
Freshwater ecotoxicity	kg 1,4-DCB	10.334238
Marine ecotoxicity	kg 1,4-DCB	58.395577
Human carcinogenic toxicity	kg 1,4-DCB	2.6683154
Human non-carcinogenic toxicity	kg 1,4-DCB	330.18233
Land use	m^2a crop eq	400.1602
Mineral resource scarcity	kg Cu eq	88.426529
Fossil resource scarcity	kg oil eq	5198.4594
Water consumption	m^3	564.27006

processing of PV waste. Laminated glass recycling facility processing does not require a dedicated recycling plant but recovers only aluminium, glass, and copper while various recoverable from solar cells are not recovered and this facility requires small batches of PV waste rather than a constant stream (Faircloth et al 2019, pp. 260–272) while FRELP method developed an Italian PV waste company SASIL S.p.a for recycling of PV is considered to be most advanced method and reduces the lifetime environmental impact by 10–15% as compared to other recycling methods is used in the present study (Latunussa et al 2016b). The system boundaries of the FRELP process (see Fig. 4) that have been taken in the present analysis exclude processing of the aluminium, glass, copper, silver, and silicon in additional plants for the production of secondary materials (Latunussa et al 2016b). The objective of this study is not only to measure the absolute values in each impact category of various disposal cases but rather to compare commonly used disposal methods to come to more definitive conclusions about how PV waste should be disposed of rationally to minimize environmental burdens.

The LCA analysis is done using SimaPro software version 8.0 (SimaPro 2021a). The ReCiPe 2016 midpoint V1.03/World (2010) method is used to analyse environmental impacts under 18 impact categories (SimaPro

Table 3 An overall impact comparison of LCIA results (SimaPro 2021a)

Impact category	Unit	Landfill (Case I)	Avoided burden approach (recycling) (Case II)	% Impact change
Global warming	kg CO_2 eq	73.7527	− 5124.95	− 22.5274
Stratospheric ozone depletion	kg CFC-11 eq	1.29E-05	− 0.00069	− 9.44294
Ionizing radiation	kBq Co-60 eq	0.169903	− 9.68052	− 8.88823
Ozone formation, Human health	kg NOx eq	0.151898	− 11.0117	− 22.8915
Fine particulate matter formation	kg PM2.5 eq	0.016694	− 3.42764	− 15.8561
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.155352	− 11.1429	− 22.1828
Terrestrial acidification	kg SO_2 eq	0.091477	− 21.9033	− 28.9246
Freshwater eutrophication	kg P eq	0.000387	− 0.60427	− 29.6695
Marine eutrophication	kg N eq	0.000167	− 0.01886	− 2.84905
Terrestrial ecotoxicity	kg 1,4-DCB	184.0005	− 6151.99	− 3.52092
Freshwater ecotoxicity	kg 1,4-DCB	0.139588	− 3.33188	− 32.2412
Marine ecotoxicity	kg 1,4-DCB	0.128903	− 20.8427	− 35.6923
Human carcinogenic toxicity	kg 1,4-DCB	0.182906	− 0.85843	− 32.1712
Human non-carcinogenic toxicity	kg 1,4-DCB	0.965908	− 37.1778	− 11.2598
Land use	m^2a crop eq	2.635054	− 137.462	− 34.3517
Mineral resource scarcity	kg Cu eq	0.035884	− 62.3286	− 70.4863
Fossil resource scarcity	kg oil eq	8.492743	− 978.131	− 18.8158
Water consumption	m^3	0.156098	− 27.0175	− 4.78804

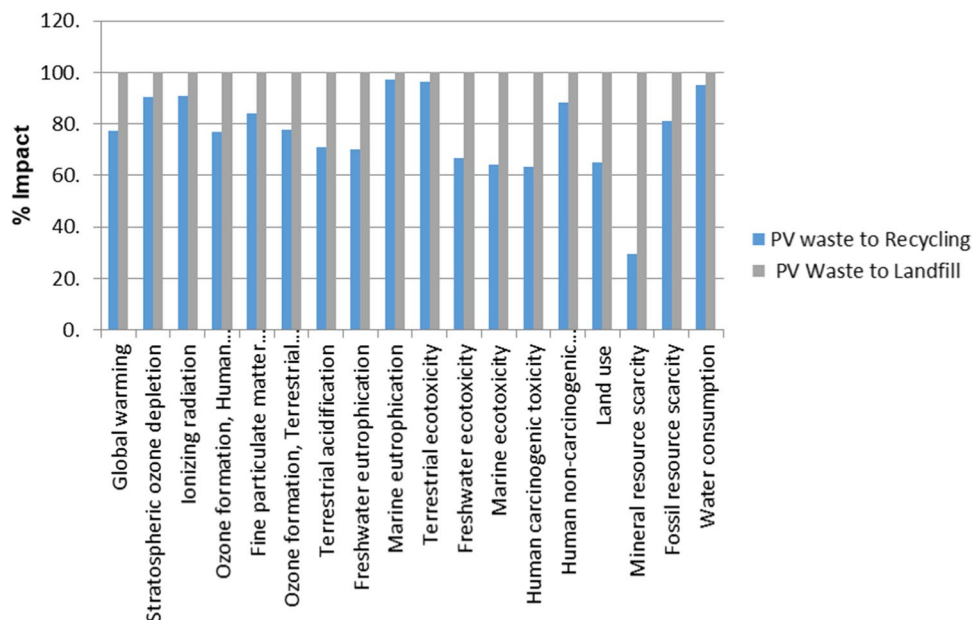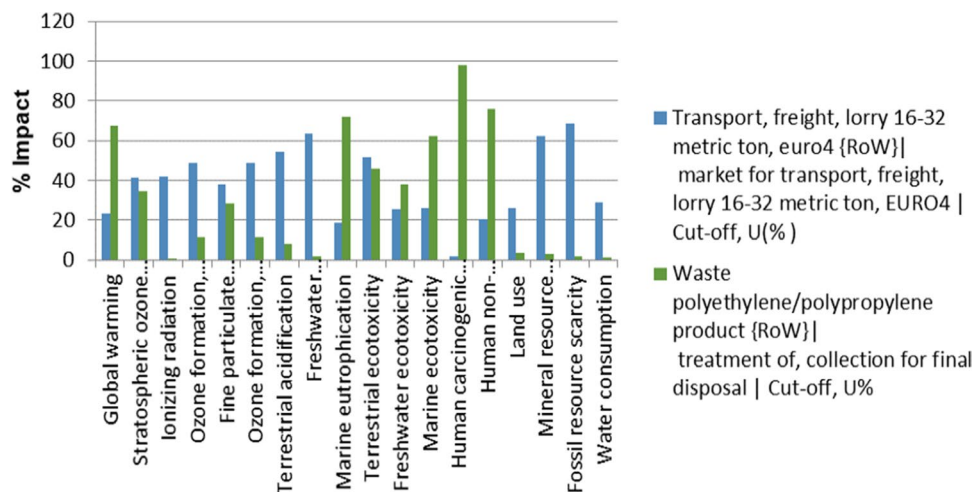**Fig. 6** Comparative illustration of LCA results

Fig. 7 Effect of transport and waste product treatment on various impact categories

2021b). SimaPro allows users to model and analyse complicated life cycles in a systematic, transparent manner in accordance to recommendations of ISO 14040 series. The input to the software is life cycle inventory (LCI) data for different cases. The present study has relied on European data set in case of the absence of a relevant Indian dataset. The LCI for the EoL phase is collated using the FRELP method. The results and their subsequent interpretation are discussed in the following section. The list of selected background input datasets used in the LCI modelling of 1000 kg solar PV waste in the present study is given in the Appendix (Table 6).

The laboratory tests provided by the FRELP are used to determine the composition of the PV module and the amount of materials that can be recovered are presented in the Appendix (Table 7). The system diagram for the FRELP process used by the SASIL group in Italy for recovering materials from 1000 kg of PV waste is given in Fig. 5 (FRELP, 2015).

The embodied energy requirement for the entire EoL treatment of c-Si PV modules is around 114 kWh/tonne of PV waste as per the FRELP process. The electrical and thermal energy quantities recovered from the incineration process of cable polymer and PV encapsulation layer are

248.84 MJ and 502.84 MJ respectively (Latunussa et al 2016a, pp. 101–111). These quantities have been credited to the FU in terms of avoided impacts on the production of electricity and heat from conventional sources.

Firstly, the LCA analysis has been undertaken to assess the impact of 1 tonne of solar panel production (72.72 m^2). The overall results from solar manufacturing impact assessments are presented in Table 2. Large amounts of energy are used to convert silica sand into the high-purity silicon required for photovoltaic wafers. The purification of metallurgical-grade (MG) silicon into electronic-grade silicon during the process of producing PV cells requires 1190 MJ/panel (Stoppato 2008, pp. 224–232). Due to the addition of high-energy content aluminium framing and glass roofing, the PV module assembly process also consumes a lot of resources. The 18 impact categories that Recipe midpoint method models to assess the potential environmental impacts are global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, human health, fine particulate matter formation, ozone formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption.

For the solar PV manufacturing process, fossil fuel and energy use impact climate change and air quality (acidification, particulate matter, etc.) as a large amount of greenhouse gas (GHG) and hazardous pollutants are released into the atmosphere. There is a large amount of consumption of energy and material such as aluminium, copper, glass, etc. The process entails the extraction of raw material, manufacture, i.e., cell–matrix production, cutting of foils and washing of glass, laminate production, isolation, and the aluminium frame of the panel.

India has no specific regulations for solar module waste disposal, thus, the main portion of solar waste is regarded as general e-waste and dumped in an unscientific manner in landfills (EU, 2021) therefore in case I, the LCA analysis has been undertaken considering that all the material at EoL goes in a landfill and impacts associated with same are studied.

In case II, avoided burden approach has been considered wherein it has been considered that solar waste materials are sent for recycling and the impact includes avoided burden due to material recycling. The recovered materials at the EoL phase are recycled back to the manufacturing phase to gauge circular economy prospects in terms of the reduction of various environmental parameters. The potential environmental impacts associated with the production of secondary material result in avoided burden as the solar PV recycling process yields recyclable materials such as aluminium, glass, copper, and other materials, the input of virgin material into the solar PV manufacturing process can be replaced with recycled material.

Results and discussion

Table 3 provides results of LCIA comparison for the case I and Case II and it can be observed from the results that impact produced under a landfill of 1000 kg c-Si PV panels produces greater environmental impacts in all 18 impact categories as compared to avoided burden approach due to recycling of materials using FRELP. The LCA analysis is done on SimaPro software version 8.0 (SimaPro 2021a) using the ReCiPe 2016 midpoint V1.03/World (2010) method to analyse environmental impacts under 18 impact categories. A list of background data sets given in the Appendix (Table 6) is used to undertake the analysis.

Figure 6 gives a comparative illustration of LCA results for the case I and case II. The major impacts associated with the case I are due to the transport and collection and treatment of waste polyethylene/polypropylene products.

Figure 7 gives a comparative percentage share due to these two parameters across all 18 impact categories and it is observed that the effect of collection, and treatment of waste polyethylene/polypropylene products under human carcinogenic toxicity is around 98%, human non-carcinogenic toxicity (76%), marine eutrophication (72%) and global warming (67%).

While the effect of transport is highest under fossil resource scarcity is around 68% freshwater eutrophication (64%), mineral resource scarcity (62%) and terrestrial acidification (54%). The overall environmental impacts are lower in all categories under case II on account of the obvious reason of recycling benefit of the material as it will result in the reduction of virgin material usage. Resource extraction and material production are some of the highest impact contributors to solar PV production, thus recycling solar PV module components can result in avoidance of the use of virgin material for production, and lesser energy and resources for extraction and further processes will be required. A ton of aluminium (virgin metal) produced in India can have GHG emissions in the range of 16–20 T CO_2 (Hindalco 2020), however as aluminium is recyclable, at EoL if aluminium products are recycled back into the manufacturing stream, the GHG emissions are reduced by 92% as the recycling aluminium requires 95% lesser energy than the virgin metal production (NITI

2019). Similarly, other materials such as glass, copper, silicon, silver etc. also require extensive energy, and recycling the material at the EoL back into the manufacturing and process stream can significantly reduce environmental impacts across all impact categories. Recycling of aluminium resulted in an 82% reduction in the stratospheric ozone depletion category, a 76% reduction across global warming, and an ozone formation category. Recycling glass resulted in a 44% reduction in the stratospheric ozone depletion category. Recycling silver resulted in an 88% reduction in the marine ecotoxicity category.

From the analysis and comparison of solar PV production and avoided burden approach due to recycling, it can be observed that recycling in the overall life cycle assessment of solar PV can result in much higher benefits for impact reduction throughout solar PV recycling. The last column of Table 3 provides a summary of % impact reduction in the solar PV manufacturing process by incorporating material recycling.

Incorporating solar PV recycling will result in an impact reduction for the solar PV manufacturing process by as high as 70%. The major reduction impacts can be seen in mineral resource scarcity, marine ecotoxicity land use, freshwater ecotoxicity and human carcinogenic toxicity categories. The impact reduction results from the aspects of avoidance of primary material production due to the recycling of solar PV components at EoL.

Nowadays, a carbon footprint, single score indicator with the application of the IPCC (Intergovernmental Panel on Climate Change) 2013, GWP model is commonly used in LCA, especially for PV panels. On basis of IPCC 2013 GWP 100a V1.03. The comparative score for solar PV manufacturing (c–Si) is 19784.976 kg CO_2 eq and the corresponding values for landfill and avoided burden approach (recycling) are 19,844.054 and 15,393.96 kgCO_2 eq respectively.

Conclusion

With ambitious solar installation targets, solar waste is bound to increase in India. The waste projection results as per the BAU scenario estimated that the PV waste could reach up to 6.64 million tonnes due to the early loss scenario and 5.48 million tonnes due to the regular loss scenario while in the ambitious scenario, the waste estimation is 10.30 million tonnes due to the early loss scenario and 8.51 million tonnes due to the regular loss scenario by the end of

2040 in India. These results of the present study vary from the results of earlier studies, mainly on account of COVID-19 pandemic disruptions, variation of t/MW factor, and the lifetime of solar panels. The PV waste if not tackled appropriately can result in a significant impact on the environment due to mishandling as well as disposal of waste in landfills. While the EU has pioneered PV electronic waste regulations including PV-specific collection, recovery and recycling other leading solar-installed capacity countries including India lack a systematic regulatory approach to handle PV waste. The present study proposes the following strategies to handle the ever-growing solar waste problem in India:

- Establishing an online monitoring system to track the flow of all discarded modules at all stages of the PV life cycle that will provide input for authorities and other stakeholders to develop regulations and policies.
- Imparting skills in PV panel repairs will enable the development of the second-hand market of solar PV modules wherein modules can be sold and purchased after doing necessary minor repairs.
- In the long term, extensive R&D will limit waste production & the establishment of pilot recycling plants to recover the secondary materials. Though, the viability of waste recovery models cannot be guaranteed owing to low to moderate values of PV waste generation. The government may therefore consider incentivizing the waste recovery units for a few initial years.
- A multi-sector and multi-stakeholder coordinated approach among various stakeholders including ministries and manufacturers along with EPR legislation that will cover the provision of collection, recovery, and recycling of solar PV.

The LCA analysis for different aspects relating to solar PV recycling and disposal was undertaken as part of the study to identify and highlight the most environmentally friendly solution for solar PV recycling. The LCA analysis has been undertaken considering that all the material at EoL goes in a landfill and impacts associated with same are studied in case I and in case II, avoided burden approach has been considered wherein it has been considered that solar waste materials are sent for recycling and the impact includes avoided burden due to material recycling. Avoided burden approach due to the recycling of materials will result in substituting virgin raw materials

with recycled materials in the forthcoming production stage will result in an impact reduction for solar PV by as high as 70%. Moreover, the reuse of recovered aluminium, glass, and silver in the manufacturing phase of the PV module will not only be beneficial from an environmental impact point of view but also from an economic standpoint. The probable sources of some of the uncertainties in the present study that may affect outcomes of solar waste estimation and its effect on the environment are discussed in the Appendix (Table 5). This study aims to apprise researchers, policymakers, and other stakeholders of impending problems that may arise due to EoL solar PV e-waste in India. Lack of infrastructure, waste handling, and recycling guidelines put India in a precarious position for achieving the twin objectives of energy security and sustainability.

The absence of availability of accurate data like life span, shape and scale parameters etc. relating to BOS is the main hindrance behind their inclusion in the present analysis. As a potential avenue of future research, the analysis carried out in the present study can be further enhanced by the inclusion of BOS along with PV modules. Another opportunity for future research lies in carrying out sensitivity and cost–benefit analysis of the recycling process.

Appendix

See Tables 4, 5, 6 and 7.

Table 4 Variation (t/MW) of Waaree solar panels (Source: Correspondence through author email)

Year	Weight to power ratio (t/MW)
2016	74.02
2017	72.05
2018	70.13
2019	68.26
2020	66.44
2021	64.67

Table 5 List of Probable source of Uncertainties in the present study

S. No	Probable uncertainties
1	Uncertainty due to projected solar PV capacity The present solar PV growth rate forms the basis of 339 GW solar PV cumulative installed capacity by 2040 in BAU scenario and the basis for 395 GW solar PV cumulative installed capacity by 2040 in an ambitious scenario is estimations provided under draft national energy policy (NITI 2017) report. Both these estimations introduce uncertainties in final PV waste figures as in the BAU scenario the installed capacity figures up to 2021 are extrapolated to obtain estimated values by 2040. In an ambitious scenario, it is difficult to judge the reliability of estimations provided in said study. The estimations provide indicative figures of waste volumes that will be generated. Further, series of Covid-19 pandemic waves are also creating uncertainty in capacity additions
2	Uncertainty due to tonnes per MW ratio With the improvement of technology PV modules are becoming lighter and lighter. The mass to power ratio till the year 2040 has been predicted from past data fitting to an exponentially decreasing curve. In the absence of availability of year-wise panel weight data in the public domain, the past data in present estimation has been obtained from a leading solar PV manufacturer in India through e mail correspondence
3	Uncertainty due to cut off point for EoL It is not necessary panels will become obsolete after 25 years and in many cases it has been observed that the PV module would still deliver enough power after their end-of-life period of 25 years. This will be more predominant in the case of solar PV panels installed at the rooftop of residential buildings. This will introduce uncertainties in the figure of waste streams
4	Uncertainty due to solar technology This study takes into consideration that c-Si technology will remain and continue to dominate the PV market in the coming years. Any significant change in the market share of c-Si technology will affect the solar waste estimation projection and LCA results. A further change in proportions of various raw materials in the PV module will affect the mass percentage of the recoverable from recycling process

Table 6 List of background input datasets used in the life cycle inventory modelling

Item	Used for the process phase	Datasets
Electricity	Solar panel disassembly, electrical cable treatment, separation of glass and refinement, PV sandwich layer cutting, sieving, acid leaching, filtration, electrolysis, neutralisation and filter press	Electricity, high voltage {IN-Western grid}| market for electricity, high voltage
Thermal energy	Heat	Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel oil, at boiler 10 kW, non-modulating
Transport	PV waste transportation to the recycling plant	Transport, freight, lorry 16–32 metric ton, euro4 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO4
	PV waste transportation to local collection point; cables transportation to cable treatment plant and cable polymer transportation to the incineration plant; transport of glass residue to landfill; PV sandwich transportation to incinerator; transport of ash to the treatment plant; transportation of fly ash to special landfill	Transport, freight, lorry 16–32 metric ton, euro4 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO4
	Sludge transportation from the recycling plant to landfills	Transport, freight, lorry 16–32 metric ton, euro4 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO4
Landfilling of the contaminated glass	Glass refinement	Waste glass {GLO}| waste glass treatment, unsanitary landfill, moist infiltration class
Disposal of fly ash in a landfill	Incineration	Fly ash and scrubber sludge {RoW}| treatment of, hazardous waste incineration
Water	Acid leaching, electrolysis, neutralisation	Water, unspecified natural origin, IN
Nitric acid	Acid leaching	Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state
$Ca(OH)_2$	Neutralisation	Lime, hydrated, loose weight {RoW}| market for lime, hydrated, loose weight
Limestone residue	Landfill	Limestone residue {RoW}| treatment of, inert material landfill
Landfilling of sludge with metal residuals	Filter press	Sludge, pig iron production {CH}| treatment of, residual material landfill

Table 7 Amount of recovered materials based on mass composition in BAU and ambitious scenario (C. E. L. Latunussa et al. 2016a, pp. 101–111)

Component	Mass composition of 1 ton of crystalline-silicon PV waste as input to the recycling process		Mass composition of PV waste as input to the recycling process				Mass composition of PV waste as input to the recycling process			
			BAU Scenario				Ambitious Scenario			
			2030 (t/MW=50.72)		2040 (t/MW=38.72)		2030 (t/MW=50.72)		2040 (t/MW=38.72)	
	Quantity	Percentage	Regular-loss scenario Quantity	Early-loss scenario Quantity	Regular-loss scenario Quantity	Early-loss scenario Quantity	Regular-loss scenario Quantity	Early-loss scenario Quantity	Regular-loss scenario Quantity	Early-loss scenario Quantity
	(kg)	(%)	(t)	(t)	(t)	(t)	(t)	(t)	(t)	(t)
Glass, containing antimony (0.01–1%/kg of glass)	700	70%	717,317	1,883,976	3,838,327	4,645,641	791,636	2,079,169	5,955,818	7,208,502
PV frame, made of aluminium	180	18%	184,453	484,451	986,998	1,194,593	203,564	534,643	1,531,496	1,853,615
Polymer-based adhesive (EVA) encapsulation layer	51	5.1%	52,262	137,261	279,650	338,468	57,676	151,482	433,924	525,191
Solar cell, containing silicon metal	36.5	3.65%	37,403	98,236	200,141	242,237	41,278	108,414	310,553	375,872
Back-sheet layer (based on Polyvinyl Fluoride)	15	1.5%	15,371	40,371	82,250	99,549	16,964	44,554	127,625	154,468
Cables (containing copper and polymers)	10	1%	10,247	26,914	54,833	66,366	11,309	29,702	85,083	102,979
Internal conductor, aluminium	5.3	0.53%	5431	14,264	29,062	35,174	5994	15,742	45,094	54,579
Internal conductor, copper	1.14	0.114%	1168	3068	6251	7566	1289	3386	9699	11,740
Silver	0.53	0.053%	543	1426	2906	3517	599	1574	4509	5458
Other metals (tin, lead)	0.53	0.053%	543	1426	2906	3517	599	1574	4509	5458
Total	1000	100%	1,024,739	2,691,395	5,483,325	6,636,630	1,130,909	2,970,241	8,508,311	10,297,859

Declarations

Conflict of interest The authors declare no competing interests.

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