Sustainable Production and Consumption 26 (2021) 65–77

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Research article

End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy

Ayush Gautam[a,*], Ravi Shankar[a], Prem Vrat[b]

[a] Department of Management Studies, Indian Institute of Technology Delhi, India
[b] The NorthCap University, Gurgaon India

A R T I C L E I N F O

Article history:
Received 21 April 2020
Revised 11 September 2020
Accepted 20 September 2020
Available online 22 September 2020

Editor: Prof. Ioannis Nikolaou

Keywords:
Circular Economy
Solar photovoltaic
E-Waste
Reverse supply chain
Recycling

A B S T R A C T

In the recent past, technological advances in the solar photovoltaic (PV) sector have accelerated, leading to managerial problems for the end-of-life (EOL) disposal of solar photovoltaic e-waste. Developed countries have initiated management systems while India is presently in the photovoltaic panel installation stage, with no concrete strategy to manage the resulting e-waste. This study undertakes an assessment of the magnitude of the issue in India, using a forecasting model that projects the amount of waste generated by EOL solar PV panels and its balance of system (BOS) using Weibull reliability function for panel failure. The study also estimates the amount of raw material recovered after recycling to contribute to the circular economy of EOL PV. In the study, an empirical estimation shows that solar PV installations in India will generate 347.5 GW by 2030. The model evaluates that between 2020 and 2047, about 2.95 billion tonnes of e-waste will be generated in India from solar PV systems, including critical metals worth 645 trillion USD, of which 70% (worth 452 trillion USD) can be recovered using state-of-the-art recycling technology. The present study sheds light on maximizing resource efficiency, by creating facilities for a circular economy-based supply chain to handle the massive e-waste generated by solar PV panels in India.

1. Introduction

The share of photovoltaic (PV) energy in the emerging electricity market is growing exponentially as it satisfies clean energy and climate policy goals and hence becomes the most competitive technology (Domínguez and Geyer, 2018). The abundance of solar energy ensures that solar PV technology, which converts sunlight directly into electricity, is a promising alternative to other electricity sources (Santos and Alonso-García, 2018). Thus, the government and private sectors are giving a considerable thrust to the technology and efficiency improvement of solar PV, ensuring a high demand for raw materials for the production of solar PV modules. However, the lack of research on the recovery of resources from end-of-life (EOL) solar PV is distressing, considering that the amount of solar PV e-waste exceeds other e-waste, with abundant base, toxic and critical materials. The assessment of the electronic waste generated by EOL solar PV is the most crucial step towards a circular economy-based policy, regulation and treatment of waste (Chaudhary and Vrat, 2017; Domínguez and Geyer, 2017; Mahmoudi et al., 2019b; Paiano, 2015; Rocchetti and Beolchini, 2015; Suresh et al., 2019). This study can also help implement measures ensuring the resource efficiency of waste electrical and electronic equipment (WEEE), with a focus on solar PV in India.

In 2016, the global PV installed capacity had already passed 500 GW and is expected to rise further to 4500 GW by 2050 (Weckend et al., 2016). According to the IRENA 2016 report, by 2030 the top three countries expected to produce cumulative EOL solar PV waste are China, Germany and Japan; by 2050, the United States of America (USA) will overtake Germany, followed by Japan and India (Weckend et al., 2016).

By examining the estimated solar potential of 750 GW in India, the 'Jawaharlal Nehru National Solar Mission (JNNSM)' was launched in 2010 to achieve the installation of 100 GW solar PV by 2022, of which 40 GW has to be rooftop solar and 60 GW has to be grid-connected. The government of India initiated many policies to achieve the target of 100 GW by 2022, with emphasis on cost reduction and efficiency growth. The government planned 41 solar parks in the country to achieve 40 GW, out of which 26 GW solar parks in 21 states have already been sanctioned (MNRE, 2018). As per the Ministry of New and Renewable Energy, India already achieved 20.81 GW solar PV installations by 31 March 2019. India

* Corresponding author.
E-mail addresses: ayush.gautam@dms.iitd.ac.in (A. Gautam), ravi1@dms.iitd.ac.in (R. Shankar), premvrat@gmail.com (P. Vrat).

https://doi.org/10.1016/j.spc.2020.09.011
2352-5509/

Nomenclature

x_i:	Amount on PV installed in year i
u_{fj}:	Power loss in year j for fixed loss
i:	The year of installation
j:	The year of waste generation
t:	time duration in year
T:	average lifetime
Υ:	shape factor
F(t):	Cumulative distribution function
u_{rt}:	The rate of power loss for regular loss after year t.
u_{et}:	The rate of power loss for early loss after year t.
U_{cj}:	Corrected power loss in year j
U_{ej}:	Early power loss in year j
α:	Technology (out of Silicon-based, CdTe, CiGs)
U_{rj}:	regular power loss in year j
$W_{j\alpha}$:	Solar panel WEEE in year j (tonne) by technology α
w:	Weight of solar panel composition in tonne/ GW for technology α
p:	Market share of technology α

Energy Security Scenarios 2047 by NITI Aayog shows the possibility of 479 GW of solar PV by 2047 (NITI Aayog, 2015). The average life of a solar panel is 25 to 30 years, thus this scale of installation will contribute to a substantial amount of waste generation in India in the near future (Domínguez and Geyer, 2017; Mahmoudi et al., 2019b; Paiano, 2015) .

The IRENA 2016 report provides the leading causes and overview of solar panel failure; they classify loss as early loss and regular loss (Weckend et al., 2016). The Raunhofer Institute conducted a study which suggests that some raw materials used in solar PV technology will start to become unavailable compared to their demand in future years, because of their limited availability and recycling infrastructure (Arora et al., 2018). At present, the issue of solar PV waste disposal is not crucial, but the management of an accumulated load of waste will be an imminent issue in India (Suresh et al., 2019). The National Institute of Solar Energy (NISE), India and the National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay conducted a survey to assess the durability, reliability and health of solar PV in different parts of India (NCPRE and NISE, 2017). Generally, countries classify panel waste as industrial waste or general waste; only the USA and Japan have specific recycling, disposal, shipment and treatment pathways for panel waste, while solely the European Union has adopted PV-specific waste regulations (Weckend et al., 2016). There is sufficient research on the recycling and reuse of electronic items like computers, mobiles and televisions. However, the disposal, recycling, managing and reuse of solar PV waste in India has not yet been quantified and analysed (Arora et al., 2018; Suresh et al., 2019). Moreover, if panels are not disposed of, this leads to environmental problems like the leaching of cadmium and lead, and the loss of metals and of conventional resources (Latunussa et al., 2016). Huge capital is associated with the waste generated from EOL PV (Contreras-Lisperguer et al., 2017), of which a sizable amount could be used after recycling (IRENA, 2017). In contemporary India, the disposal of EOL PV is preferable to recycling (Arora et al., 2018; Suresh et al., 2019). However, a secondary material supply chain of recovered materials can be established by recycling (Mahmoudi et al., 2019a; Prajapati et al., 2019; Santos and Alonso-García, 2018). For this, it is essential to estimate and quantify the time needed and the amount of materials which can be recovered from PV waste. The solar PV industry is not immune to economic crises, given India's evident dependence on imports, primarily of copper, silver and gold. In recent years, the demand for silver in India has increased exponentially. To fulfil the requirement, 5,000 tonnes of silver have been imported, and merely 400 tonnes of silver have been produced domestically (Arora et al., 2018). A material flow analysis of EOL solar e-waste and materials required to produce the PV modules is crucial for designing techniques and strategies to handle EOL waste (Paiano, 2015). Moreover, some precious and critical metals form a smaller mass share of the waste, but their contribution to waste is significant considering their economic value. Hence, it is essential to study the economic significance of every metal (Mahmoudi et al., 2019b). Definitively, there is a significant need for a circular supply chain for managing EOL solar PV WEEE and for recovering resources by recycling e-waste, to balance the economic structure (Chaudhary and Vrat, 2017). The following research questions are therefore raised:

(a) What is the amount of EOL electronic waste generated by PV solar panels and its balance of system (BOS) in India?
(b) How can circular economy issues for solar PV e-waste be taken care of?

The following objectives are framed to answer the above questions:

1 To measure the failure of the PV module based on the reliability of panels.
2 To provide a forecasting model that estimates the amount of waste generated by EOL solar PV systems.
3 To estimate the raw material recovery and analysis of economic gain after recycling, to maximize the resource efficiency of EOL solar PV waste.

The present study helps in designing a circular economy-based reverse supply chain of resources in India and contributes towards the sustainable management of PV technologies (Arora et al., 2018; Chaudhary and Vrat, 2017). Projections of solar PV installation capacity for this study are made by observing the trends and projection of solar panel installations by the IRENA, The Energy Resource Institute (TERI), NITI Aayog, Bridge to India (BTI) and JNNSM reports. The model presented in the paper estimates solar PV and its BOS waste by the deployment of 347.5 GW solar panels by 2030 to calculate the amount of material that could be recovered from it, by designing a reduce, reuse, recycle (RRR) road map of solar PV e-waste (Dwivedy and Mittal, 2012; Lopes de Sousa Jabbour et al., 2019). The present research considers early and regular panel failures as per the Weibull reliability function, which is a versatile and tested methodology for measuring solar PV failure rate (Weckend et al., 2016); here, both fixed loss and the Weibull reliability approach with India's specific early failure rate parameter are used for estimating the waste generated by solar PV and its BOS. Results show that a significant amount of EOL panel waste already hit the country in early 2019 and is increasing at an exponential rate. This study considers the waste originated by 2047 as per the projected installation of panels by 2030. This study also accounts for an economic assessment of metals, annual recycling targets and the requirement of raw materials to make perfect balance for precious, toxic and critical materials (Domínguez and Geyer, 2018; Mahmoudi et al., 2019b; Sarath et al., 2015). This study analysed 21 metals present as a resource in PV WEEE and their recycling. The framework of the study is structured as shown in Fig. 1. Firstly, the growth and projections of solar PV installations in India by 2030 are analysed, and the amount of waste is quantified using the methodology and data explained in Section 2. The model estimates the amount of different materials contained in solar PV which will convert into waste, along with their recycling and economic analysis. This is followed by results and discussion in Sections 3 and 4 respectively. Managerial recommendations from the present research are presented in Section 5. Finally, the conclusion is provided in Section 6.

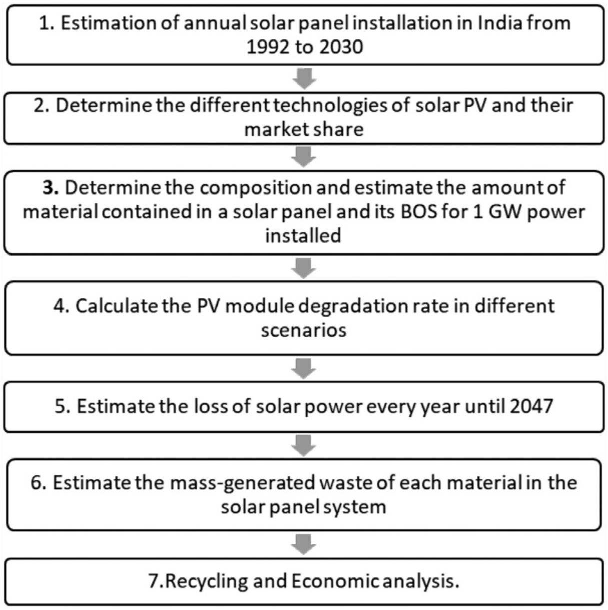

Fig. 1. Methodology flow chart for estimating recovered materials from Solar PV Installation.

2. Methods

A PV system comprises of interconnected PV modules, inverters, transformers, cabling, and mounting structures. It may also have optional batteries for energy storage purposes in case of off-grid systems, and tracking systems for improving the sunlight capture. These additional components to PV panels can be named the balance of system (BOS) (Domínguez and Geyer, 2018, 2017; Mahmoudi et al., 2019a, 2019b). This study considers three different types of schemes for energy loss and waste estimation every year due to the failure of panels: early loss, fixed loss and regular loss; these failures refer to the damage of panels before, at and after the average life of the panel respectively (Mahmoudi et al., 2019a). The present research considers panels' early and regular failures as per the Weibull reliability function, which is a versatile and tested methodology for measuring solar PV failure rate (Weckend et al., 2016). Domínguez and Geyer estimated the EOL PV panels and their BOS loss for USA and Mexico by using the fixed loss methodology (Domínguez and Geyer, 2018, 2017), while Santos and Alonso-García and IRENA used the Weibull reliability function for estimating the repowering need and EOL waste without considering BOS (Santos and Alonso-García, 2018).

This section is further divided into seven parts as shown in Fig. 1. Subsections 2.1, 2.2 and 2.3 focus on arranging, sorting and converting necessary data required by the model for estimating the material inventory of EOL solar PV waste and the material inventory required every year for the installation of solar PV. Subsections 2.4, 2.5 and 2.6 estimate the amount of waste which needs to be disposed of, managed or recycled every subsequent year. Here, the annual and cumulative waste streams in India as a function of the market share of PV technologies are calculated in tonnes produced per GW of PV installed. Subsection 2.7 deals with recycling and economic analysis to assess the amount of recovered resources from the EOL solar PV.

In this study, the amount of waste is calculated until the year 2047, which will further be benchmarked with the Indian energy scenarios 2047 by NITI Aayog. Moreover, JNNSM policy is planned for 2022, which will complete its 25 years of panel life in 2047 followed by a technology change. Also, until 2047, the majority of waste generation (97%) is based on generations one and two of the solar panels followed by generation three (2047 onwards), so the calculation of waste by 2047 is a more practical estimation and provides a better range of options for future exploration (Islam & Huda, 2018; Mahmoudi, Huda, & Behnia, 2019).

Table 1
Solar panel technology classification (Arora et al., 2018).

Technology	Cell Type
Silicon based	Monocrystalline Poly or multicrystalline Ribbon a-Si (amorph/micromorph)
Thin-film based	Copper indium gallium (di)selenide (CIGS) Cadmium telluride (CdTe)
Other	Concentrating solar PV (CPV) Organic PV/dye-sensitised cells (OPV) Crystalline silicon (advanced c-Si) CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V

2.1. Estimation of annual solar panel installation in India from 1992 to 2030

Actual installed solar power capacity for India from 2010 to 2019 with projections until 2030 by different agencies is shown in Table A.1. As per the IndiaStat, in 1992 the concept of solar energy installation gained popularity in India but grew at a very slow rate. According to the report *Transitions in Indian Electricity Sector 2017–2030* by The Energy Resource Institute (TERI), if India follows the high renewable energy scenario (HERS), the installed capacity will reach around 534 GW by 2030, while it will reach around 161 GW if India follows the low renewable energy scenario (LERS) (NCPRE and NISE, 2017). Actual PV installation data until 2019 was collected from the MNRE portal. Projections of this study are benchmarked against the IRENA, TERI, NITI Aayog, Bridge to India (BTI) and JNNSM reports as presented in Table A.1. The trend follows the S-type curve from 1992 to 2047 as shown in Fig. 2, and clearly explains the exponential growth of PV technology installation from 1992 to 2047 in India.

This S-shape growth rate of solar PV installation will continually require base, precious and other raw materials for the manufacturing of panels, while maintaining cost competitiveness. Hence the concept of a circular economy and resource efficiency (RE) becomes important (D'Adamo et al., 2020; Govindan et al., 2015; Suresh et al., 2019).

2.2. Determine the different technologies of solar PV and their market share

PV panels can be classified based on the technology used, as shown in Table 1. The different technologies of solar PV vary in terms of materials used and the composition of precious and hazardous substances (Latunussa et al., 2016). The market share of each technology varies by innovation and time, as shown in Table A.2. As the market share of other technologies is very much less and they are under the umbrella of Si-based and thin-film technology, three different PV technologies are considered in this study: Si-based, CdTe and CiGs (Contreras-Lisperguer et al., 2017; 2009; NISE, 2018). For calculation purposes, the market share of technology in 2020 was taken as 89% for Si-based, 5.2% for CdTe and 5.2% for CiGs (Weckend et al., 2016). The average life of solar panels increased from 25 years to 30 years in 2014, as shown in Table A.2 (Arora et al., 2018; Domínguez and Geyer, 2017; ITRPV, 2019)

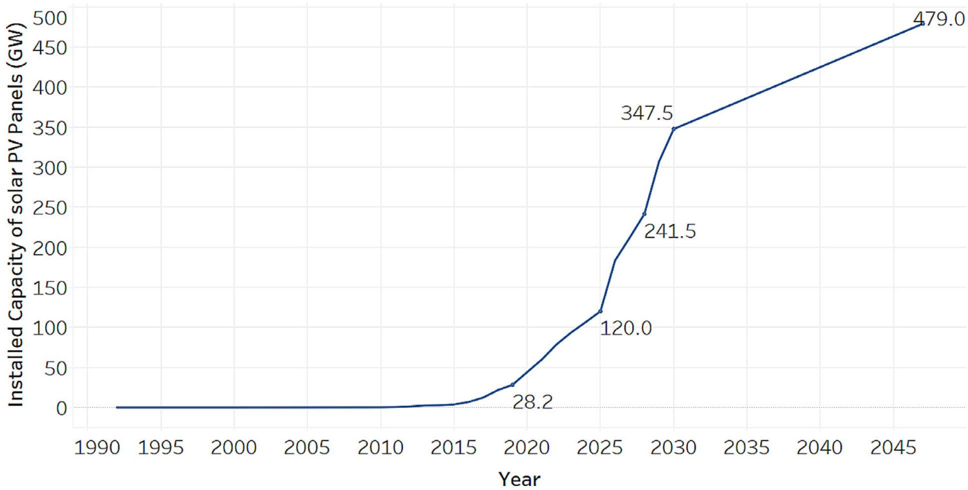

Fig. 2. Trend of Solar power (GW) installation in India by 2047 (MNRE, 2018; NCPRE and NISE, 2017; TERI, 2015).

Table 2
Specifications of PV panels (Domínguez and Geyer, 2018, 2017; Mahmoudi et al., 2019b; Santos and Alonso-García, 2018).

PV Technology	Area (m^2)/nominal power	Area (m^2)/GW	Nominal Power (W)	Weight(tonne)/ GW	Market Share (%)
Si based	1.46	6517857	224	102678.5	89
CdTe	0.72	11076923	65	184615.4	5.2
CiGs	0.72	9000000	80	157500	5.8

2.3. Determine the composition and estimate the amount of material contained in a solar panel and its BOS for 1 GW power installed

Crystalline silicon-based technology is leading the market share of solar PV installation across the world contemporarily. These panels have precious, base, critical and hazardous waste as shown in Table 3 and has specific recycling procedure (Ashfaq et al., 2017). The main components of which are copper, aluminium, glass, silver, silicon and Ethylene vinyl Acetate (EVA) (Arora et al., 2018).

Specifications like area, mass, nominal power, market share all the PV technology which are used for the forecasting of waste mass in a tonne for 1 GW installation are shown in Table 2. The material compositions of all PV technology are converted into tonne/ GW for the calculation purposes.

Table 3 further classify panel components in precious, special, toxic, critical and other criteria. This data is taken from various sources (Domínguez and Geyer, 2018, 2017; ITRPV, 2011; Paiano, 2015; Santos and Alonso-García, 2018) and by questionnaire survey from industry experts.

In this study, inverter, cable, and mountings are primarily considered as integral part of BOS while transformer and battery as external part of BOS. Most of the PV systems are grid-connected thus need of converting direct current generated by panels into alternating current makes the inverter one of the essential part of PV system.

This paper analysed a string inverter of 500 kW with an inverter sizing ratio of 1.15 (Domínguez and Geyer, 2018; Mahmoudi et al., 2019b), material inventory of which is developed from Ecoinvent database 3.3 (Domínguez and Geyer, 2017). The cables connect a solar panel to the transformer, inverter and combiner box. Solar PV cable generally use Cu or Al as a conductor; this study assumes copper as a conductor with the amount of 0.64 Kg/m^2 of PV module or 4712.07 tonnes Cu for 1 GW solar PV installed (Domínguez and Geyer, 2017). Mounting structures are used to provide support and base to solar PV; they are generally made of aluminium and copper. The Table 3 shows the material composition of BOS based on the Ecoinvent database 3.3. The transformer is also one of the critical components of PV system. Usually, the power factor of the transformer used in solar PV is 0.8 (D'Adamo et al., 2017). Generally, components used in the transformer are Fe and Al or Cu where Al transformer weights 45% of the Cu transformer. Other components like battery and tracking systems could also be part of BOS which are out of the scope of this study as these components already have stabilised recycling infrastructure. Here all the mass calculations are being converted for 1 GW solar power installed. The average life of an inverter is taken as 10 years, while the average life of other BOS is 25 years (TERI, 2015).

2.4. Calculate the PV module degradation rate in different scenarios

The fixed loss scheme assumes that the panel comes to the EOL after a fixed time period and then the panel is replaced; this is calculated by equation (1). The average life of the system is considered 25 years by 2014 and 30 years after this, as per the IRENA 2016 report (Weckend et al., 2016). Here it is assumed that the panel is directly replaced after EOL, so

$$u_{fj} = x_i \tag{1}$$

where the year of installation ‘i’ varies from 1992 to 2030, while the year of waste generation ‘j’ varies from 1992 to 2047. For fixed loss,

$$j = i + t;\ t = 30 \text{ if } i > 2014;\ t = \ 25 \text{ if } i \leq 2014.$$

However, due to the uncertainty of the phenomenon, the exact time of panel failure cannot be determined, and degradation of the panel counts as a temporary phenomenon, so there is a need to calculate the probability distribution function for determining the reliability of the panel. The IRENA 2016 report provides the main cause and overview of solar panel failure; they classify PV losses as early loss and regular loss. The probability of loss in both scenarios can be calculated by the Weibull reliability function as shown in equation (2), and the model suitability for modelling the failure of the panel was previously shown in the cited literature (Mahmoudi et al., 2019b; Santos and Alonso-García, 2018;

Table 3
Mass of all the components in solar PV system (tonne/ GW) (Domínguez and Geyer, 2018, 2017; ITRPV, 2019; Mahmoudi et al., 2019b; Paiano, 2015; Santos and Alonso-García, 2018, 57a).

Metals	Element	Mass composition PV Technology (tonne/GW)			Mass composition PV BOS (tonne/GW)			Recycling Yield (%)	Cost USD/tonne
	Technology	Si based	CdTe	CiGs	Inverter	Cabling	Mounting		
Precious Metals	Ag	57.96	0	0	2.13	0	0	95	651000
	Au	0	0	0	2.94	0	0	36	49375000
Base and special metals	Al	16557.9	166.16	13590	753.25	0	25423.5	100	2000
	Cr	0	33.24	0	0	0	0	20	9900
	Cu	736.64	5538.47	450	1949.25	4712.07	0	100	6460
	Sn	0.06	0.01	90	0.06	0	0	32	19340
	Zn	0.01	0.01	90	2.3	0	1760.09	27	2610
	Ti	0.01	0.01	0	0	0	0	52	640
	Ta	0	0	0	0.12	0	0	21	194000
	Mn	0	0	0	0.01	0	0	37	5
	Mo	0	0	90	0	0	0	18	17800
	Fe	0	0	0	0.29	0	48891.4	90	600
	Ni	1.07	0	0	0.92	0	0	41	14520
Other metals	Si	795.31	553.85	0	0	0	0	100	29998
Toxic/hazardous metals	Pb	4.7	7.76	0	10.35	0	0	98	2320
	Se	0	0	90	0	0	0	89	50300
	Cd	0	221.54	270	0	0	0	95	1100
Critical metals	Te	0	221.54	0	0	0	0	95	89000
	Mg	522.82	0	423	0.06	0	0	33	2010
	Ga	0	0	90	0	0	0	90	295000
	In	0	0	45	0	0	0	90	460000
Other materials	EVA	6518.86	6646.16	8100	0	0	0	0	890
	Glass	65840.46	168369.2	135000	0	0	0	95	790

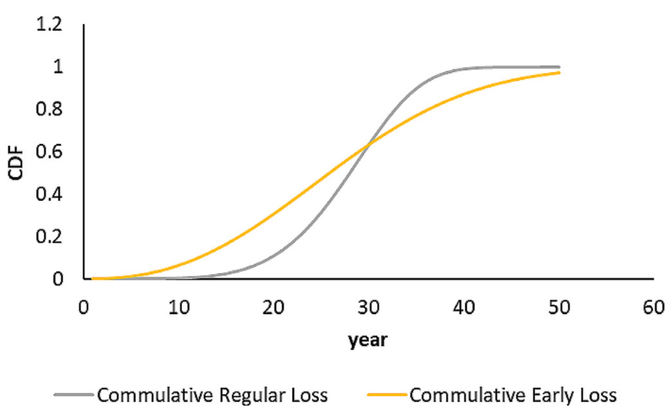

Fig. 3. Weibull cumulative distribution function for regular loss and early loss for the given parameters (Weckend et al., 2016).

Weckend et al., 2016). The shape factor ϒ defines the evolution of failure of the panel with time t; the baseline value of ϒ is taken as 5.3759 for regular loss scenario and 2.4928 for early loss scenario, while both scenarios assume life loss of 99.99% probability in 40 years with 30 years of an average lifetime; the ϒ value for solar PV was taken from International Energy Agency Photovoltaic Power Systems Programme and other resources cited (Mahmoudi et al., 2019b; Santos and Alonso-García, 2018; Weckend et al., 2016). The cumulative distribution function of Weibull function is given as

$$F(t) = 1 - e^{-\left(\frac{t}{T}\right)^{\Upsilon}} \tag{2}$$

Where "*t*" the time duration in year varies from 0 to 40. Shape factor "ϒ" controls the typical S shape of the Weibull curve. F(t) is the cumulative distribution function of Weibull function; its curve is shown in Fig. 3.

So,

For regular loss,

$$u_{rt} = F(t) \text{ with } Y = 5.37 \tag{3}$$

For early loss,

$$u_{et} = F(t) \text{ with } Y = 2.4928 \tag{4}$$

NISE, India and NCPRE, IIT Bombay inspected 925 modules at 37 sites in all the 6 climatic zones of India and comes out with average early loss failure rate of 1.55% per year (NCPRE and NISE, 2017). As the failure rate and degradation of panels varies for country and location, so u_{et} for India is given as

$$u_{et} = x_i(1 - \ 0.0155\ )^t \tag{5}$$

early loss every year is calculated as a combined effect of equation 4 & equation 5, while regular loss as a combined effect of equation1 and equation 3.

2.5. Estimate the loss of solar power every year until 2047

This section corresponds to objective 1 of the research. The corrected loss for every year was calculated as the combined effect of early and regular loss for the corresponding year, as shown in equation 5. Corrected loss corresponds to the repowering need every year, and its amount would also increase exponentially. Corrected loss is given as

$$U_{cj} = U_{ej} + U_{rj} \tag{6}$$

Where *i* varies from 1992 to 2030 and *j*=*i*+*t*.

2.6. Estimate the mass-generated waste of each material in the solar panel system

This section corresponds to objective 2 of the research. Once the above five steps were carried out, the total PV system waste mass and year-wise material inventory required and recovered from waste can be calculated by equation (7), where the total energy loss of each year multiplied by the mass composition of each material and the market share of each particular technology, as shown in sections 2.4 and 2.2 respectively:

$$W_{j\alpha} = U_{cj} w_{\alpha i} p_{\alpha} \tag{7}$$

The corrected loss of each year was multiplied with the mass of material shown in Table 3, to estimate the share of each metal and material in PV EOL waste.

2.7. Recycling and Economic analysis

This section corresponds to objective 3 of the research and sets the road map for a circular economy. The recycling of PV waste is still at its nascent stage globally, both in terms of physical infrastructures and technical standards. This would lead to the designing of necessary policies to ensure diversion of this WEEE stream from the mainstream and also social and economic cost benefits, while creating sustainable conditions and infrastructure for the proper treatment of solar PV WEEE stream (Corcelli et al., 2017; Saxena, 2017). India has no specific regulations for solar module waste disposal. Recycling references for solar thermal power plants can be found in MNRE's guidelines, which state that the developers are to ensure that all solar PV modules collected from their plant after their EOL are disposed of as per the 'E-waste (Management and Handling) Rules' published by central government and amended from time to time. However, neither waste module is covered in these guidelines nor there are there any specific mechanisms. India is not very efficient when it comes to e-waste management, even though the rules and policies for e-waste handling and management were first published in 2011 and then amended in 2016 and 2018 by the Ministry of Environment, Climate Change and Forecast (Dwivedy et al., 2015; Suresh et al., 2019). In April 2019, the MNRE issued a blueprint for the disposal, utilization, manufacturing and import of solar PV. Data from CPCB shows that the country can theoretically handle only 22% of the total e-waste generated in the country, and actual capacity is even less.

A high cost is associated with waste generated from EOL PV (Contreras-Lisperguer et al., 2017), a large part of which can be used after recycling (IRENA, 2017). So, to calculate the amount of secondary material recovered from waste, the amount of material waste is multiplied by the recycling yield of the corresponding material. Considering both present and future technologies, Domínguez and Geyer and Santos and Alonso-García did extensive research to find out the recycling yield of all metals present in PV systems, as shown in Table 3. The recycling yield of materials is taken from the various literature (Domínguez and Geyer, 2018, 2017; Latunussa et al., 2016; Mahmoudi et al., 2019b; Paiano, 2015; Santos and Alonso-García, 2018).

Moreover, some precious and critical metals have a lower share in the waste, but their contribution to waste is significant considering their economic value, so it is equally important to study the economic significance of every metal. The market values of different metals are taken from the literature review, money control web pages and other sources (Domínguez and Geyer, 2018; Islam and Huda, 2019).

3. Results

An analysis of EOL PV between 2020 to 2047 is carried out in this section. Cumulative estimations of EOL waste in India were calculated while taking account of all the major solar projects in India as per JNNSM. The projection of annual solar PV installations considered to 2030 is based on various reports and forecasts, while the amount of annual EOL waste is estimated to 2047. The estimation of year and amount of disposal of waste every year helps in designing a circular supply chain for EOL waste (Chaudhary et al., 2017; Chaudhary and Vrat, 2018a, 2018b). These calculations are based on two fundamental assumptions. Firstly, the silicon PV technologies will continue to dominate the PV market in the future. Secondly, the proportions and mass of raw material in the PV module system will remain constant with time. Further, the sensitivity analysis sections demonstrate that the amount of waste and the recovered secondary resources are subject to change with the change in technologies of PV modules, recycling yield, their market share, metal compositions and installation rate in-country.

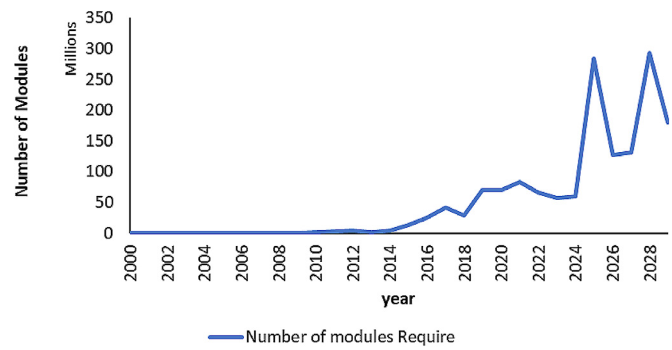

Fig. 4. Estimated number of modules required for PV installation by 2030.

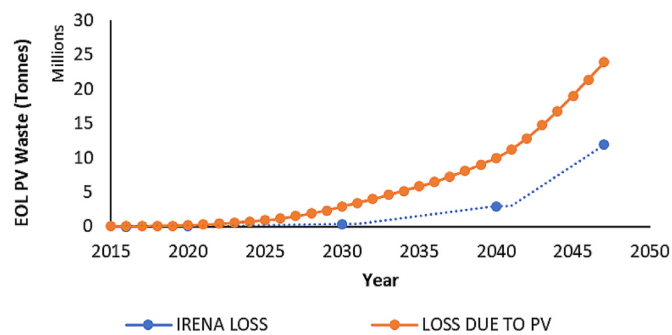

Fig. 5. Comparison of estimated solar PV panel EOL waste with IRENA waste by 2047.

3.1. Material requirement for the estimated solar energy demand

Based on the estimated cumulative installation of 347.5 GW by 2030, the annual capacity installed, number of modules, number of inverters and precious elements (Ag, Au) required every year are calculated as shown in Table 4, which provides a brief idea of the material inventory in subsequent years. Fig. 4 shows the trajectory of the number of modules required every year for the estimated PV installation of 347.5 GW by 2030. Here the requirement of all the components of solar PV also follows the same trajectory. Around 3.7 million inverters will be required in 2028. India will require approximately more than 2 billion modules and 20 million inverters by 2030, as well as2,472 tonnes of silver and 1,390 tonnes of gold. PV panels account for 70% of the total waste, while 30% of the waste comes from BOS. This is the reason why this study considers not only PV waste but its BOS waste also, which includes mounting structures, inverters and cabling.

3.2. Waste and material Inventory

The comparison of estimated EOL PV power loss with the power loss mentioned in the IRENA 2016 report for India is shown in Fig. 5. It can be observed that the amount of waste in the future is considerably more than that expected by IRENA, because India further improved its solar installation targets of JNNSM in 2014 from 20 GW to 100 GW. Also, India has a high rate of early failure because of poor handling. IRENA calculations of waste due to early failure are based on the Weibull reliability function, while India follows a constant average failure rate, as discussed in Section 2. Fig. 6 displays the loss of PV power installed, with early loss, fixed loss and regular loss between 1992 to 2047; corrected loss is the sum of early loss and fixed loss calculated as in equation 6. Here, losses are directly proportional to the amount of waste generated, which shows the need for repowering. Results show that

Table 4
Estimated inventory required for solar PV installation by 2030.

Year	Annual Installed Capacity (GW)	Cumulative Installed capacity (GW)	No. of Module Required	No. of Inverter Required	AG Mass Required (tonnes)	Au Mass Required (tonnes)
2000	0.01	0.01	17858	230	0.54	0.03
2001	0.01	0.02	40179	518	0.27	0.02
2002	0.01	0.02	17858	230	0.92	0.05
2003	0.02	0.04	66965	863	0.66	0.04
2004	0.01	0.05	44643	575	0.99	0.06
2005	0.02	0.06	66965	863	1.34	0.07
2006	0.02	0.08	89286	1150	1.4	0.08
2007	0.02	0.1	89286	1150	1.49	0.08
2008	0.02	0.12	89286	1150	1.59	0.09
2009	0.02	0.14	89286	1150	1.77	0.09
2010	0.03	0.17	93750	1208	18.08	0.92
2011	0.3	0.47	1339286	17250	44.21	2.24
2012	0.75	1.21	3321429	42780	66.72	3.38
2013	1.12	2.32	4973215	64055	22.35	1.14
2014	0.32	2.64	1397322	17998	70.95	3.59
2015	1.12	3.75	4964286	63940	184.73	9.35
2016	3.02	6.77	13477679	173593	335.94	17
2017	5.53	12.29	24669643	317745	569.04	28.8
2018	9.37	21.66	41794643	538315	423.9	21.45
2019	6.53	28.18	29147322	375418	986.95	49.95
2020	15.82	44	70625000	909650	1021.34	51.69
2021	15.75	59.75	70312500	905625	1247.18	63.11
2022	18.75	78.5	83705358	1078125	1097.89	55.56
2023	15	93.5	66964286	862500	1062.44	53.77
2024	13	106.5	58035715	747500	1182.3	59.83
2025	13.5	120	60267858	776250	4181.61	211.6
2026	63.5	183.5	2.83E+08	3651250	2310.48	116.92
2027	28.5	212	1.27E+08	1638750	2549	128.99
2028	29.5	241.5	1.32E+08	1696250	4839.37	244.88
2029	65.5	307	2.92E+08	3766250	3650.72	184.74
2030	40.5	347.5	1.81E+08	2328750	1595.96	80.76

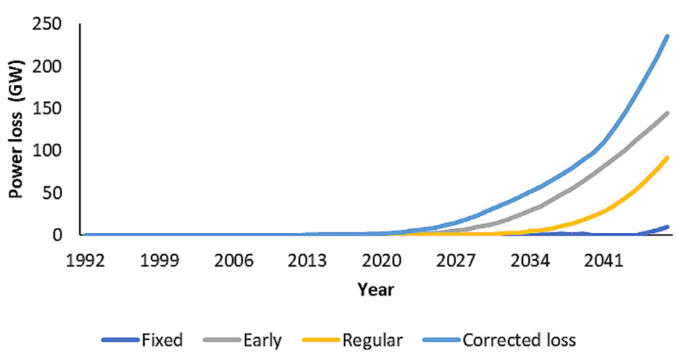

Fig. 6. Year wise PV repowering requirement due to different losses.

the amount of waste originating from early losses is at a higher rate than regular losses, while waste due to the fixed loss scheme is proportional to the installation rate. The waste due to Weibull's regular loss is always less and follows Weibull's early loss while India's specific rate of early loss passes Weibull's early loss in 2040 as per the estimated projection of installation by 2030. Taking account of the total number of modules, inverters and precious metals required as shown in Table 4 and considering the given market share and materials used, the amount of EOL solar PV e-waste generated by 2047 is displayed in Fig. 7 and Table 6.

The total estimation of waste between 2020 to 2047 is 2.95 billion tonnes; Fig. 8 and Table 6 classify waste in terms of generation by PV installation or generation by BOS, and show the amount of silver and gold available for disposal and recycling every year.

A significant amount of waste already hit the market in 2019 and then increases exponentially to 35 million tonnes by 2050. Fig. 7 shows that the EOL PV waste stream will start affecting the country significantly in the next five years and will exponentially increase; therefore, now the right time for recycling industries to investigate the infrastructure set up to address the future problem.

In Fig. 8, it is underlined that 59% of total waste is expected from the most popular silicon-based modules, 6% from the CdTe module, 2% from the CiGs module, whereas 7% of waste is from inverters and 26% from cable and mountings. The BOS of solar PV may have other devices also which are not considered in this study. Also, the continuous growth of the waste mass share of CdTe and CiGs technology is observed after 2045 because of technological advancement.

Further, Table 6 classifies an estimated 2.9 billion tonne metal inventory and its comprehensive compilation between 2020 and 2047 corresponding to projected PV installation by 2030. This waste includes PV and BOS. Fig. 9 shows the estimated percentage of all major components used in EOL PV system waste including glass and EVA. These are mainly glass for covering purposes (51%), aluminium for module frames (31%), EVA for panel lamination (5%), copper for cabling (6%) and silicon for PV module cells (1%). Figs. 10 and 11 show the contrast between the requirement of precious materials by 2030, waste generated and the amount of precious metals recovered i.e. Ag and Au respectively, by 2047. Fig. 10 clearly shows that due to the high recycling yield of silver, almost 95% of silver can be recovered from inverters and EOL PV panels, which would itself be able to compensate for a major part of silver demand in the future. Similarly, a significant amount of gold can be recovered from EOL solar PV inverters. India is heavily dependent on imports when it comes to precious and rare earth

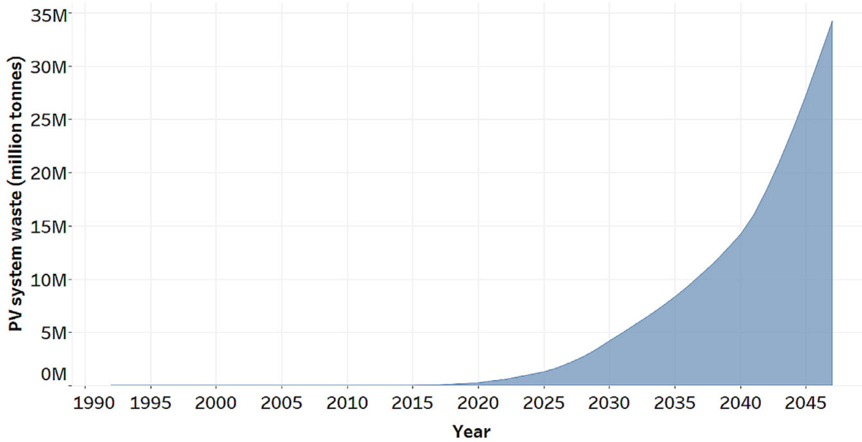

Fig. 7. Estimated cumulative EOL PV system waste (million tonnes) from 1992 to 2047.

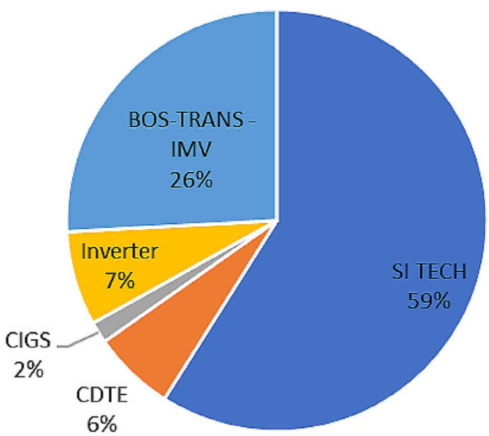

Fig. 8. Estimated mass share of components and technology in EOL PV panels between 2020 and 2047.

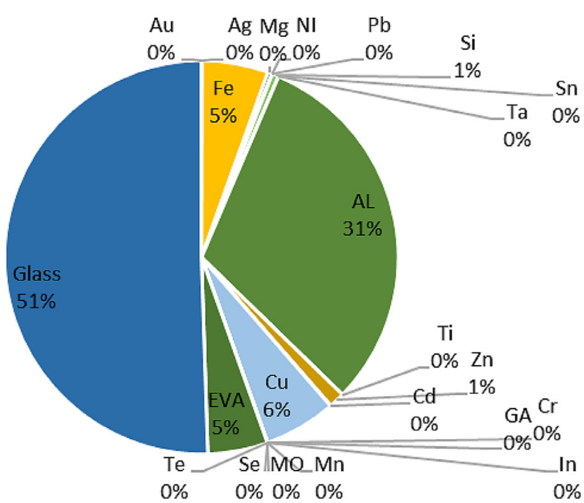

Fig. 9. Estimated mass share of materials in EOL solar PV systems between 2020 and 2047.

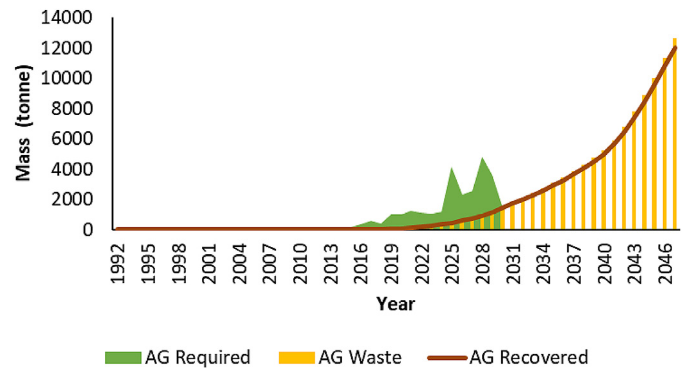

Fig. 10. Trends of silver mass as waste generated and recovered by 2047 and required by 2030.

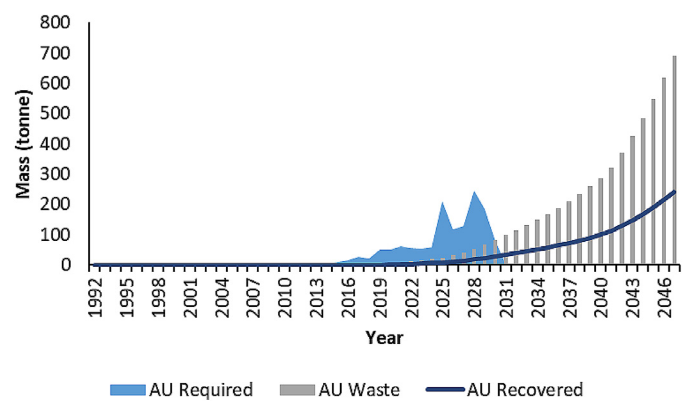

Fig. 11. Trends of Gold mass as waste generated and recovered by 2047 and required by 2030.

materials, hence the special focus required. Figs. 12 and 13 present the waste scenario of toxic and critical materials respectively.

3.3. Recycling and Economic analysis of Metal Inventory

Recycling yields are estimated for around 21 metals in this study; this comes in the range of 60% to 97% for the entire solar cell. The recycling yield for BOS is reported as 90%. Recycling is crucial to conserve mineral resources and to avoid environmental pollution. Table 5 further underlines the metal inventory share of the PV system as per their economic value and mass. Also, it shows the mass and economic value of all the metals recovered after recycling. Fig. 14 underlines the economic analysis of PV system waste components. Economic analysis shows that the value of total waste emerging from 2020 to 2047 is around 645 trillion US$ as per the present commodity price, of which 70% of the cost (453 trillion US$) can be recovered if state-of-the-art recycling techniques are used. This makes recycling very necessary and reasonable for EOL PV waste. Table 5 and Fig. 14 clearly signify that

Table 5
Estimated weight and economic share of metals in EOL PV system waste generated in India between 2020 and 2047.

Metal	Mass Share (tonne)	Mass Share (%)	Price (USD/tonne)	Commodity Value (USD)	Economic Share (%)	Mass Recovered (tonne)	Economy recovered (USD)	MASS loss (tonne)	Money loss (USD)
Au	5678.36	0.01	49375000	280368.8	43.93	2044.21	100932.7	3634.15	179436
Ag	103992.1	0.09	615000	63955.15	10.02	98792.5	60757.38	5199.61	3197.75
Fe	14231361	12.21	600	8538.8	1.34	12808225	14089.05	1423136	853.88
Mg	948608.4	0.82	2010	1906.71	0.3	313040.8	629.22	635567.6	1277.49
NI	3608.2	0.01	14520	52.4	0.01	1479.37	21.49	2128.84	30.91
Pb	29678.67	0.03	2320	68.86	0.02	29085.1	67.48	593.58	1.37
Si	1426346	1.23	2998	4276.19	0.67	1426346	4276.19	0	0
Sn	10209.35	0.01	19340	197.45	0.04	3267	63.19	6942.36	134.26
Ta	222.69	0.01	194000	43.21	0.01	46.77	9.08	175.92	34.12
AL	80783049	69.28	2000	161566.1	25.32	80783049	161566.1	0	0
Ti	9.03	0.01	640	0.01	0.01	4.7	0.01	4.34	0.01
Zn	3422732	2.94	2610	8933.34	1.4	924137.6	2412	2498594	6521.33
Cd	52630.07	0.05	1100	57.9	0.01	49998.57	55	2631.51	2.90
Cu	15526872	13.32	6460	100303.6	15.72	15526872	100303.6	0	0
Cr	3345.94	0.01	9900	33.13	0.01	669.19	6.63	2676.76	26.45
GA	10107.76	0.01	295000	2981.79	0.47	9096.99	2683.62	1010.78	298.18
In	5053.89	0.01	460000	2324.79	0.37	4548.5	2092.31	505.39	232.48
Mn	11.14	0.01	5	0.01	0.01	4.12	0.01	7.02	0
MO	10107.76	0.01	17800	179.92	0.03	1819.4	32.39	8288.37	147.53
Se	10107.76	0.01	50300	508.43	0.08	8995.91	452.5	1111.86	55.92
Te	22305.93	0.02	89000	1985.23	0.32	21190.63	1885.97	1115.3	99.26
Total	1.17E+08	100	51161103	645397.4	100	1.12E+08	452335.9	4593324	193061.5

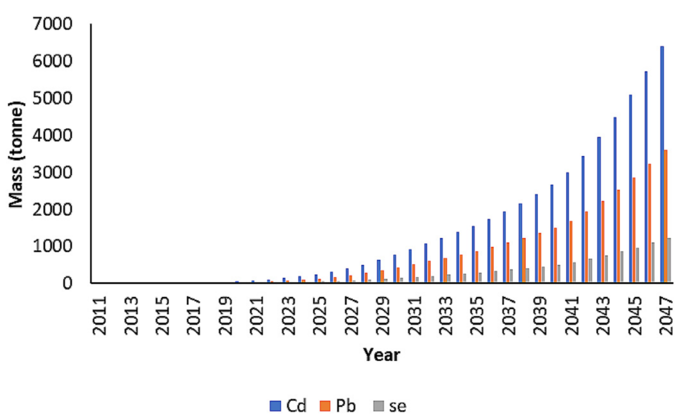

Fig. 12. Different toxic metals generated by 2047 by EOL solar PV systems.

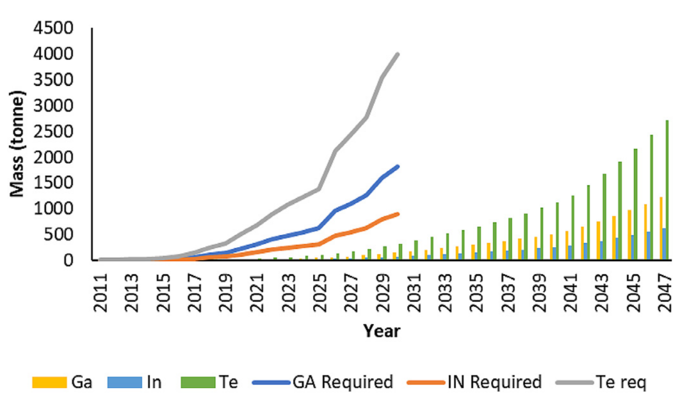

Fig. 13. Trends showing critical material waste generated by 2047 and critical material required by 2030.

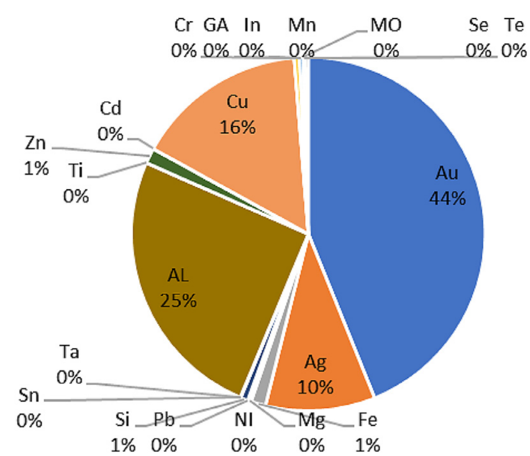

Fig. 14. Estimated economic share of metals in PV system waste between 2020 and 2047.

the main contributor resources from an economic point of view are gold (44%), aluminium (26%), copper (16%) and silver (10%). It is observed that most of the economic value is captured by precious and base metal waste. Moreover, critical metals like gallium, magnesium, indium and tellurium do also have a noticeable economic presence. Precious metals have a high economic value and are rare too; silver is used in the C-Si solar cells of the PV modules and both silver and gold are used in the inverters. This study analysed 5,678 tonnes of gold and 103,393 tonnes of silver used in PV systems. Table 5 also shows the weight and economic loss of all the metals due to a lack of efficiency in recycling technologies.

3.4. Sensitivity analysis

The estimation of the amount of waste and the recovered secondary resources is subject to change with improvements in the technologies of PV modules, their market share, metal composition, in-country installation rate and recycling yield. The forecasting model present in the study is robust enough to incorporate these changes. Table 6 demonstrates that although the current market is dominated by Si-based PV modules, with the flow of time, the market share of thin-film and advanced Si-based panels will have significant value. The estimated value of the market share in 2030 is 79.9% for Si-based, 4.7% for CdTe and 15.7% for CiGs technologies, as the metal composition of other technologies is still unknown, as it is distributed among three major and basic technologies (Domínguez and Geyer, 2018). This type of technolog-

Table 6
Estimated Power loss (GW), material loss and precious metal loss (tonnes) between 2020 and 2047.

Year	Corrected loss (GW)	Total waste (tonnes)	Total Waste PV (tonnes)	Total Waste BOS (tonnes)	AU Waste (tonnes)	AG Waste (tonnes)	AU Recovered (tonnes)	Ag Recovered (tonnes)
2020	1.89	287527.8	191700.5	94776.49	5.54	101.33	1.94	96.27
2021	2.8	425410.1	283629.4	140226	8.19	149.93	2.87	142.43
2022	3.98	606185.3	404155.8	199814.1	11.67	213.63	4.09	202.95
2023	5.39	820775.5	547227.4	270548.5	15.8	289.26	5.53	274.8
2024	6.99	1064557	709761.1	350904.9	20.49	375.17	7.17	356.41
2025	8.79	1339373	892986.9	441491.5	25.78	472.02	9.03	448.42
2026	11.58	1764172	1176209	581516.1	33.95	621.72	11.89	590.64
2027	14.81	2256046	1504151	743650.2	43.42	795.07	15.2	755.31
2028	18.5	2817757	1878655	928804.3	54.23	993.02	18.98	943.37
2029	23.22	3538092	2358917	1166245	68.09	1246.88	23.83	1184.53
2030	28.6	4358149	2905665	1436557	83.87	1535.88	29.36	1459.08
2031	34.04	5187141	3458370	1709813	99.82	1828.03	34.94	1736.62
2032	39.59	6031796	4021519	1988233	116.08	2125.69	40.63	2019.41
2033	45.28	6899871	4600282	2274373	132.78	2431.62	46.48	2310.03
2034	51.2	7801322	5201297	2571514	150.13	2749.3	52.55	2611.83
2035	57.42	8750001	5833800	2884223	168.38	3083.63	58.94	2929.45
2036	64.01	9753298	6502718	3214935	187.69	3437.2	65.69	3265.34
2037	71.76	10934991	7290577	3604451	210.43	3853.65	73.65	3660.97
2038	79.42	12102949	8069277	3989440	232.9	4265.25	81.52	4051.99
2039	88.73	13521617	9015132	4457069	260.2	4765.21	91.07	4526.95
2040	97.94	14924224	9950278	4919404	287.19	5259.51	100.52	4996.53
2041	109.93	16751648	11168658	5521769	322.36	5903.52	112.83	5608.34
2042	126.71	19308296	12873226	6364505	371.56	6804.52	130.05	6464.29
2043	145.15	22118326	14746729	7290763	425.63	7794.81	148.97	7405.07
2044	165.28	25186987	16792667	8302272	484.68	8876.25	169.64	8432.44
2045	187.12	28514961	19011493	9399256	548.72	10049.07	192.06	9546.62
2046	210.63	32097243	21399872	10580068	617.66	11311.52	216.18	10745.94
2047	235.73	35922315	23950124	11840909	691.26	12659.53	241.94	12026.55
Total		295085030.7	1.97E+08	97267531	5678.5	103992.2	1987.55	98792.58

ical advancement results in a 22% increase in the amount of waste, while the amount of silver decreases by 10%. Further, as the share of silicon-based technology decreases, this would result in a decrease in the requirement for silicon, magnesium and aluminium, while thin-film modules increase the requirement for critical metals like selenium, indium, gallium etc. The recycling yield shown in the study is based on advanced technology used in the USA. Data from CPCB shows that India does not have enough infrastructure for recycling; the country can handle only 22% of the total e-waste. Therefore, the amount recovered shown in the study is the maximum possible yield that could be recovered; the real recovery will be even less. However, as these recycling technologies for most of the materials are relatively new, the actual materials recovered are a little less. The transformer is an integral part of the solar PV system: the Cu-Fe transformer is used for most of the calculations, as Cu resources have more constraints and are more economical than Al. If aluminium conductors are used in transformers instead of copper, then the share of aluminium increases, while the share of copper used and the amount of total waste decrease by a significant value, because the weight of Al-Fe transformers is equivalent to 45% of that of Cu-Fe transformers. Moreover, technology advancements will further reduce and change the number of components used. This will change the share and quantum of components in EOL solar PV waste and would require further advancements in recycling technologies (Domínguez and Geyer, 2017). Latunussa et al.'s (2016) results show that the collection and transport of EOL solar PV waste from the sites, incineration and other treatments (including acid leaching, sieving, electrolysis and neutralization) will also affect the recovery of metals.

4. Discussion

The result of this study has a significantly higher magnitude of EOL PV waste than the IRENA study, because PV installed has increased by five times as per the latest policy and has a higher early loss rate in India as explained by Figs. 2 and 5. This scale of installation requires a considerable material inventory and other resources for manufacturing the solar PV and its BOS, as shown in Tables 3 and 5 and Fig. 4. The estimated waste in this study can be compared with the IRENA, EU REI and BTI report which deal with EOL solar panel waste. In this study, loss is calculated according to the market share of the technology and reliability as per the exponential Weibull function. Results shows that about 2.95 billion tonnes of e-waste will be generated in India between 2020 and2047 from solar PV systems, including special, precious and critical metals. It is underlined in Fig. 8 that BOS accounts for approximately 30% of the total waste generated by solar PV systems.

EOL solar PV waste has just started impacting Indian market in 2020 as shown in Fig. 7 and Table 6, and its growth will be exponential. A significant amount of e-waste will has generate in all areas of the country as presented in Table 5 and Figs. 10–12. This evaluation of the materials and waste generated from the Indian PV stream installation is considerably higher than any other WEEE, which will be difficult to dispose of if the country does not have infrastructure to manage it. This provides clear insight for authorities to investigate the recycling and management of EOL solar PV waste. The mass and economy share of all the 21 metals and other components present in EOL solar PVs is demonstrated in Table 5, Figs. 9 and 14. Economic analysis shows that the value of the total waste to be generated from 2020 to 2047 is around 645 trillion US$ as per the present commodity price, of which 70% of the cost (453 trillion US$) can be recovered if a state-of-the-art recycling technique is used. This value is much higher than the IRENA estimation of the monetary value of recovered material from PV waste by 2030 (Weckend et al., 2016) because India has further improved its solar installation targets of JNNSM in 2014 from 20 GW to 100 GW, and because the country has a high rate of early failure due to poor handling. This makes EOL PV waste recycling both crucial and reasonable. Although introducing breakthrough technologies for recycling and using recycled material from solar PV e-waste for manufacturing present a great challenge, there is an urgent need for such infrastructures, as extreme demands for raw materials in the future could be fulfilled by secondary raw materials, thus reducing import dependency. It also solves the eventual problem of scrap and disposal handling, otherwise panel components made of lead, cadmium and other hazardous metals need to be treated separately.

In the present scenario, none of the PV manufacturing and recycling industries are prepared for handling PV waste in India. The country is poorly positioned to handle solar PV waste as it does not have any guidelines and policies (Arora et al., 2018). They are still managed under the umbrella of e-waste rules 2011; the lack of a policy framework leads to a lack in proper recycling infrastructure. As per CPCB, the country is able to recycle less than 4% of estimated e-waste in the organised sector (D and D, 2020; Suresh et al., 2019).

The results shows that although a major part of PV EOL waste is captured by base metals such as aluminium, copper, zinc, iron and silicon, a special focus is also required for precious, toxic and hazardous materials. Toxic materials are mainly used in thin-film panels, while small quantities of critical materials are mainly used in PV modules, but their political and economic fluctuations will always be a constraint on the supply (Domínguez and Geyer, 2018). Requirements for these materials in India between 2020 and 2030 are shown in Figs. 12 and 14. Gallium and other critical metals are strategic in nature and most countries do not have primary resources (Brininstool, 2015; Despeisse et al., 2017); also, India is almost fully dependent on imports of precious metals (Gupta et al., 2016). This study does not include repowering needs, otherwise, the amount of cumulative raw materials required and EOL PV WEEE in 2047 will further increase by a significant amount.

The model presented in the study is robust and flexible enough to incorporate all the BOS, technology share, recycling yield, economic value and their instant change as presented in the sensitivity analysis. Here, it is assumed that the silicon PV technologies will continuously dominate the PV market in the future, and that the proportions and mass of raw materials in PV module systems will remain constant with time.

The forecasting model estimates EOL PV waste and solar power loss due to panel failure; this can help in performing analysis for annual repowering needs, materials required and readiness for handling waste. For the same, the most preliminary and proactive requirement is to monitor the waste stream in terms of quality and quantity. To establish a monitoring system, the first stage is to develop relevant regulations and policies followed by a proper circular economy-based reverse supply chain (Kalmykova et al., 2018; Seuring and Müller, 2008). PV waste can be considered as a secondary mining industry, because of the huge market and variety of metals. To utilize these metals properly, there is a need for a circular supply chain network to transfer waste to recycling centres without any potential environmental impact.

4.1. Managerial recommendations of the present research

This section highlights managerial contributions required to develop an EOL e-waste infrastructure in India with a special focus on solar PV e-waste.

4.1.1. Managerial and Policy recommendation

The present study has important operational and regulatory recommendations for the solar PV recycling industry and policy makers involved in the development of electronic waste management infrastructure. The following insights are highlighted based on the present study:

- As per the calculation of the present study, the volume of EOL solar PV system waste generated in the country is significant in 2020 amounting to 0.29 million tonnes, so the industry needs to start setting up a proper solar panel recycling infrastructure for modules and other BOS components;
- The total EOL solar PV system waste of 2.95 billion tonnes will be expected by 2047. To establish a monitoring system to handle this much e-waste, immediate efforts are required to develop a dedicated circular economy-based reverse supply chain for PV e-waste;
- Economic analysis shows that the value of total solar PV e-waste emerging from 2020 to 2047 is around 645 trillion US$ as per the present commodity prices, of which 70% of the cost (452 trillion US$) can be recovered if state-of-the-art recycling techniques are used. Therefore, material flow analysis and regular inspections of recycling facilities are required to improve and understand capacity levels and technology.

4.1.2. Theoretical recommendations for future studies

Based on the present research, the following implications are highlighted for the management of EOL solar PV system waste:

- The results of this study can be considered a benchmark for future researchers to make a more comprehensive analysis of EOL solar PV e-waste.
- This study can help in implementing measures to ensure the resource efficiency of WEEE with a focus on solar PV.
- The model present in the study can be used as a reference for other developing nations to estimate the amount of EOL solar PV waste generated.
- The study can further help decision-makers and researchers to explore the field, and also act as a database for future development of a circular supply chain, economic feasibility studies and life-cycle analysis of EOL solar PV waste in India.

4.2. Recommendation for implementing a circular economy for EOL solar PV in India

Reusing and recycling EOL components have considerable benefits not only for the environment but for the economy as well. The true potential of a circular economy for EOL management is yet to be explored in many sectors (Kumar and Dixit, 2018; Mangla et al., 2018). There is a need for a business model to tackle circular economy-based reverse logistics, EOL waste management for efficient material recovery and process re-engineering. To justify circular economy claims, the solar industry needs to adopt a circular supply chain approach for EOL recycling (Rahman and Subramanian, 2012). A circular economy for solar PV can be achieved by life-cycle assessment, material substitution, diversity and cross-sector linkages, and by tax credits and subsidies in bio-based materials. Further, a circular economy in the design of solar PV can be achieved by design for disassembly, recycling, modularity and customization, while a circular economy in manufacturing solar PV can be achieved by reproducible and adaptable manufacturing, material productivity and energy efficiency (Changwichan and Gheewala, 2020). A circular economy in the collection and disposal of solar PV can be achieved by Extended Producer Responsibility (EPR), incentivized recycling, reverse logistics infrastructure building and a take-back system (Batista et al., 2018; Guldmann and Huulgaard, 2020; Howard et al., 2018). Recycling and recovery of solar PV can be made circular by cascading, downcycling, substance recovery and energy recovery (Kalmykova et al., 2018; Korhonen et al., 2018). . Also, the easily dismantled and standardized design of solar panels and BOS can make the recycling circular (Lopes de Sousa Jabbour et al., 2019). Liability and responsibility for handling waste management and treatment should be specified to each stakeholder of the solar PV value chain

(Singhal et al., 2019; Suresh et al., 2019). There is a need to need to strengthen EPR schemes and PRO (Producers Responsibility Organisations) to handle EOL PV waste.

5. Conclusions

This study apprises researchers of problems that may arise due to EOL solar PV e-waste in India. Lack of recycling guidelines and infrastructure puts India in a poor position to handle solar PV waste. The results of our study estimate that solar PV and its BOS will produce around 2.95 billion tonnes of waste by 2047; this waste will consist of 51% glass for covering purposes, 31% aluminium for module frames, 5% EVA for panel lamination, 6% copper for cabling and 1% silicon for PV module cells. The waste components are made up of 21 metals with a total commodity price of US$ 645 trillion, the main contributors of which are gold (44%), aluminium (26%), copper (16%) and silver (10%). The results show that resources worth US$ 452 trillion can be recovered from EOL waste using state-of-the-art recycling techniques. The present study discussed establishing a monitoring system to handle this much e-waste, for which immediate efforts are required to develop a dedicated circular economy-based reverse supply chain for PV e-waste. For such an ecosystem, a business model is needed to take care of the circular economy of EOL solar PV waste for efficient material recovery and process re-engineering. The study could help decision-makers and researchers to explore the field and will also act as a database for future development of a closed-loop supply chain, economic feasibility studies and life-cycle analysis. This study could be further extended to perform classifications of metals present, a material flow analysis and a cost–benefit analysis for the smooth collection, disassembly and recycling of e-waste.

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.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors thank the five anonymous referees for their constructive suggestions.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2020.09.011.

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