Life Cycle Assessment of Solar Photovoltaic in India: A Circular Economy Approach

Vishnu S Prabhu¹ · Shraddha Shrivastava¹ · Kakali Mukhopadhyay^{1,2}

Received: 25 May 2021 / Accepted: 28 July 2021 / Published online: 18 September 2021
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2021

Abstract

This pioneering work employs the attributional and comparative life cycle assessment methodology to evaluate India's ambitious target of installing 100 GW of solar energy by 2022 and the FREL method to study the circular economy prospects of the substantial PV waste it is expected to generate. Business as usual projections suggest that the intended target will be achieved no sooner than 2029. The lower lifetime of polycrystalline PV modules combined with their lower efficiency is found to severely downgrade their environmental performance vis-à-vis monocrystalline PV modules. The end-of-life treatment of the projected 6,576 tonnes of solar PV waste, expected to be accumulated between 2034–59, indicates a recovery rate of 90.7% entailing electricity consumption, GHG emissions, and monetary cost of 678.6 MWh, 648 tonnes of CO₂ eq., and USD 11.8 billion, respectively. Simultaneously, the recovery of aluminum and glass alone leads to a direct saving of 70.3 GWh of energy by eliminating raw material extraction and processing. Further, the economic value of the recovered material at USD 11.74 billion is found to have the potential to generate additional solar capacity worth 19 GW. However, making the end-of-life treatment of PV waste financially feasible would require government subsidization. A minimum amount that would equate the costs to the benefits is USD 690/MW. The study, therefore, intends to inform potential stakeholders about the environmental burden as well as the economic potential of the impending PV waste and concludes with important policy prescriptions for enabling a sustainable energy transition through the circular economy approach.

Keywords Circular economy · Solar photovoltaic · Life cycle assessment · Solar PV recycling · FREL

JEL Code Q42 · Q47 · Q53

✉ Kakali Mukhopadhyay
kakali.mukhopadhyay@mcgill.ca

Introduction

India, one of the largest economies in the world with a fast-growing population, demands higher energy security in order to achieve sustainable economic growth. The country's per capita electricity consumption has increased from 15.6 kWh in 1950–51 to 1,208 kWh in 2019–20 [1]. The Government of India's endeavor to provide 24x7 Power for All is in accordance with the Sustainable Development Goal (SDG) of ensuring access to affordable, reliable, and sustainable energy for all [2]. With India achieving 100% rural electrification along with rising incomes over the last few decades, more and more households have access to basic amenities which require electric power, such as television, refrigerator, and computers [3]. The country is also committed toward the adoption of cleaner energy sources in its energy mix under the landmark Paris Agreement, thereby simultaneously contributing to SDG Goal 13¹. As per one of the Nationally Determined Contributions (NDCs) under the stated agreement, India is required to increase its non-fossil fuel share of cumulative power generation capacity to 40% by 2030 [4]. With more than 60% of the current installed power capacity being dominated by thermal energy sources, India plans on meeting this target by embarking upon the world's largest renewable energy (RE) capacity expansion program of achieving 175 GW RE installed capacity by 2022. This target is further split into 100 GW solar, 60 GW wind, 10 GW bio-power, and 5 GW small hydro [5]. Of the 100 GW solar energy target, 60 GW is to be achieved through utility-scale ground-mounted PV and 40 GW through rooftop PV. With a potential solar RE capacity of 750 GW and more than 5,000 trillion kWh/year energy incident over the country's land mass, the prime importance accorded to solar energy in India's RE energy mix is in accordance with the multiple factors favoring its exponential growth [6, 7].

The adoption of Solar Photovoltaic (PV) systems is considered to be a highly sustainable solution for tackling adverse environmental consequences and has accordingly registered phenomenal growth in the recent past [8]. The solar PV technology itself has matured over time and currently possesses a wide range of technology options within it. These technologies mainly differ in terms of the light-absorbing materials used and include wafer-based cells (traditional mono-crystalline, poly-crystalline, micro-crystalline silicon, or gallium arsenide), commercial thin-film cells (cadmium telluride, amorphous silicon, and copper indium gallium diselenide), and new thin-film technologies (perovskites, organic materials, and quantum dots) [9]. The characteristics of PV module technologies largely remain the same across regions, however, the exact values vary due to differences primarily in solar-irradiance, module performance ratios, energy requirement, as well as the type of PV systems such as ground-mounted PV or rooftop PV. Today, the crystalline silicon (c-Si) PV technology led by monocrystalline (m-Si) and polycrystalline (p-Si) PV modules is dominating the solar PV market primarily because of its proven field stability and high conversion efficiency levels provided by silicon [10, 11].

The positive environmental impact of solar power generation in terms of greenhouse gas (GHG) emissions reduction has been elaborated extensively in the literature [12–15]. However, despite its huge potential for emission reduction, solar electricity generation systems are not actually emission-free technologies as they carry the environmental weight of other phases in the life cycle [16]. One of the key assessment tool instrumental in directing attention toward this aspect is the Life Cycle Assessment (LCA) methodology, a technique for assessing various aspects associated with the development of a product and its potential impact throughout a product's life [17]. Ludin et al. [18] review solar PV LCA studies conducted between 2000 and

¹ SDG Goal 13 – taking necessary action against climate change and its impact.

2016 and summarize that GHG emissions for m-Si PV modules range from 29 – 671 gCO_{2eq}/kWh and from 12.1 – 569 gCO_{2eq}/kWh for p-Si PV modules. Meanwhile, the average energy requirement levels of c-Si PV modules range from 150 kWh/m² – 1845 kWh/m², whereas for thin-film amorphous PV modules, it ranges from 50 kWh/m² – 400 kWh/m² [19]. The harmonized median estimates for GHG emissions from m-Si and p-Si PV technologies stand at 40 gCO_{2eq}/kWh and 47 gCO_{2eq}/kWh, respectively. Similarly, the harmonized median estimates by mode of installation amounts to 48 gCO_{2eq}/kWh and 44 gCO_{2eq}/kWh for ground-mounted and rooftop c-Si PV systems, respectively [20].

One of the major limitations of the previous LCA studies is that while they consider indirect emissions from upstream processes such as materials extraction, transportation, and plant construction, only a few of them consider indirect emissions from downstream processes such as plant decommissioning, recycling of materials, and waste disposal. The reason cited for this is that GHG emissions of solar PVs are heavily weighted toward upstream operation [20]. This is also the reason why some studies assume that at the end of its technical life the system is landfilled without any material or energy recovering process [16]. Going forward, however, downstream processes are poised to become a major cause of concern for the global community. With the demand for solar PV panels increasing progressively year after year, the volume of decommissioned PV panels is supposed to rise too. By 2030, the Asian economies, currently exhibiting higher growth of solar PV, are collectively expected to generate 55.8 MT of solar PV waste compared to 40.8 MT in Europe by 2040. Thus, ensuring that energy transition is complemented by a transition to a circular economy through strategies such as reducing, reusing, recycling, and recovering is a prerequisite for sustainable energy transition. Embedding the circular economy approach in the solar PV lifecycle can prove to be the most effective way to improve the modules' environmental performance by reducing the energy input in the manufacturing phase of the modules, which is the most energy-intensive phase of the solar PV lifecycle [21–23].

Nikolau, Jones, and Stefanakis [24] provide a comprehensive overview of the concepts of circular economy and sustainability at the micro-, meso-, and macro-levels across engineering/natural sciences and management/economic sciences. With the help of extensive literature review, the authors find an increasing trend in academic research in this field over the past decade where the concepts of circular economy and sustainability are found to be mutually inclusive in nature. In recent studies, higher emphasis has been provided at the macro-level focusing on urban, regional, and national policies with more studies being conducted in the engineering/natural sciences field. The notion of circular economy in developing countries was given very little attention previously due to the lack of knowledge regarding the benefits such as the increase in productivity and economic growth, employment generation, and curbing ill-effects on the environment [25]. Investments in product and process technologies for disposal and management of industrial waste recycling by the private sector and providing funding for innovations and developing product standards by national and local governments will contribute toward transitioning toward a circular economy across various sectors. For instance, in the case of solar PV panels, it has been recommended that the preparation for recycling of PV waste should be manifested in the production phase itself where the PV design can be made in such a way that at the end-of-lifetime it is easier to decommission PV modules for recycling and reuse [26]. Reusing and recycling PV panels at their end of lifetime can unlock a large stock of raw materials and other valuable components. A 40% reduction in the environmental burden was documented while investigating the prospects of a solar energy system based on reused components for developing countries, attributed to the absence of battery production impacts [27]. Similarly, the potential recovery of silicon from PV waste is

expected to reduce the cumulative demand for silicon from 17 Mt to 13.4 Mt by 2040 in Italy, where the high demand for c-Si technology modules has increased demand for high-purity silicon [28]. Analogously, by 2050, PV waste mining could provide 72–80% of the raw material required to manufacture the Spanish demand of PV modules that year [29]. Even in South Korea, with proper monitoring, collection, and storage of PV waste arranged shortly post-production, the recycling treatment can yield high commercial value for materials recovered from the 4.4–5.8 million tons of PV waste expected to be accumulated by 2080 [26].

However, the global status of practice and knowledge for the end-of-life management of crystalline silicon PV modules, especially in the developing countries, is still in its infancy and demands investment in research and development to reduce recycling costs and environmental impacts compared to disposal, while maximizing material recovery [30]. Assuming the latest recycling technology available in Mexico, 75% of 1.2 MT of PV waste expected to be generated by 2045 can be recovered and reused for PV manufacturing [31]. However, Mexico currently does not have the capacity to adopt high-end technologies to achieve this target. Similar is the case for all developing and underdeveloped countries, including India. IEA suggests that by 2050, global PV panel waste is projected to increase to 60–78 million tons while the recoverable value from PV waste could cumulatively exceed USD 15 billion, equivalent to the amount of raw materials needed to produce approximately 2 billion panels, or 630 GW of power-generation capacity [32]. This suggests that the Solar PV has immense potential for accelerating the transition from the conventional linear to the new circular economy concept such that energy resources are retained as available for use in the production cycle for as long as possible, by maximizing economic benefits and minimizing the environmental impacts [33]. In order to harness such a huge potential, strategizing comprehensive policies at the national level becomes important. This would in turn require careful investigation into the dynamics of the solar PV industry to explore the environmental and economic prospects of recycling practices through techno-economic analyses and LCAs to optimize solutions and minimize trade-offs [30].

While all the studies discussed thus far are in the context of other countries, a recent study analyzing the circular economy potential from solar PV waste in the end-of-life (EoL) phase in India was undertaken by Gautam et al. [34]. The study uses a forecasting model to project the amount of waste generated by EoL solar PV panels and its balance of system (BOS) using Weibull reliability function for panel failure. For this purpose, the study estimates the annual solar PV installation until 2030. The authors show that 347.5 GW of solar PV installations by 2030 is expected to generate 2.95 billion tonnes of e-waste between 2020 and 2047 with potential recovery of critical metals worth USD 452 trillion at EoL. All these elements form a critical element of the objectives of the present study as well. However, this study goes well beyond its predecessor to undertake a more comprehensive target-based analysis. The broad objectives and the accompanying novelties of this study are listed below:

- (1) This pioneering work investigates the circular economy prospects of the world's largest solar capacity expansion in India throughout its lifetime. The LCA analysis is inclusive of upstream as well as downstream activities as the exclusion of the latter is a significant research gap in the literature. To this end, an attributional and comparative LCA is undertaken, to understand the energy and environmental impact of ground-mounted and rooftop solar PV installation using m-Si and p-Si PV technologies at the national level
- (2) The comparative LCA presented in this study is a novelty in itself, as the literature on LCA of solar PV technology in India remains scattered, limited to a particular solar PV plant in a particular region, with no distinction made between different PV technologies [35, 36]. This

study, therefore, attempts to provide a generalized national level framework for studying the energy and environmental impact of solar PV for power generation

- (3) The study presents a timeline for the probable achievement of the intended target based on which the projections of impending PV waste from the proposed capacity expansion are made. In doing so, this study provides an update to the projection made by IRENA and IEA PVPS [32] by factoring in the impact of the COVID-19 pandemic. Furthermore, an extension is provided to this study, and other studies estimating the annual and cumulative PV waste generation [37, 28, 31, 34, 38] by estimating the financial costs of recycling as well as the economic value of recovered materials, thereby assessing the PV capacity which can be installed with the help of resale of recovered materials in the Indian context
- (4) The work comparable to this study is a recent collaborative report on PV waste management in India [39]. While the report provides insights into the recycling rates of various PV waste materials at the end-of-lifetime, the cost of recycling these materials across various stages considers only private costs in terms of transportation, treatment, landfilling costs, etc. The present study goes beyond this constraint to include the external costs in terms of negative environmental impact from the recycling process
- (5) Additionally, the cumulative breakdown of the type of materials which can be recovered and reused at the end-of-lifetime as well as the energy and environmental gains from substituting virgin material manufacturing with recovered material is estimated
- (6) Finally, based on the cost-benefit analysis of the PV waste recycling process, the study proposes a minimum threshold for subsidizing PV waste recycling that the policymakers should consider in order to make the process financially viable in India

Thus, this study provides a comprehensive evaluation of the circular economy prospects of solar photovoltaic compared to the existing studies in literature.

The rest of the paper is organized as follows: First, the Materials and Methods section briefly describes the Indian solar PV industry and the trend of solar PV deployment followed by defining the goal and scope of the LCA study along with the Life Cycle Inventory (LCI) analysis. Next, the study provides the Life Cycle Impact Assessment (LCIA) across the economic, energy, and environmental dimensions. This is followed by the interpretation of these results and the conclusion and policy recommendations at the end of the paper.

Materials and Methods

The Indian Solar PV Industry

Evolution of Installed PV Capacity in India

The development and incorporation of solar PV technology were discussed for the first time among Indian policy-makers as early as the 3rd Five Year Plan (1961–66) [39]. Since it was a completely new technology at that time, its incorporation in the Indian power sector was not a natural development. It was only twenty years later in the 6th Five Year Plan (1980–85) that the implementation of solar power capacity for electricity generation was discussed and a Commission for Additional Sources of Energy (CASE) was set up. Soon, the National Solar Photovoltaic Energy Demonstration Program (NASPAD) was implemented under which manufacturing of solar PV cells and modules of 10.35 kW, 21.07 kW, and 31.75 kW was achieved for the first time.

In 2010, the government announced the Jawaharlal Nehru National Solar Mission (JNNSM) under the National Action Plan on Climate Change (NAPCC-2008) under which a target of 22 GW of grid-connected and off-grid power plants was expected to be achieved by 2022 [39]. Though a very conservative target, this was the first national-level solar capacity installation program pursued by the government. Subsequently, the new government in 2015 increased the solar capacity installation target to 100 GW to be achieved by 2022.

By 2014, the cumulative solar installation in the country could reach 3.2 GW only [41]. However, following the announcement of the national RE expansion program in 2015, solar installations saw exponential growth, as demonstrated in Figure 1.

The highest increase in solar installations of 9.7 GW was witnessed in 2017 which corresponded to a 123% year-on-year increase. Since then, the solar industry has witnessed a negative capacity installation growth rate, which can be attributed to the economic slowdown, liquidity crunch, as well as the COVID-19 pandemic [45].

As of December 2020, only 38.4 GW of the 100 GW target was achieved, implying that by the end of 2022, a total of 61.7 GW or approximately 30 GW installations per year is required. Table 1 gives the share of rooftop PV and ground-mounted PV installation yet to be achieved.

With an average of 6.5 GW installation achieved in the last five years and the slowdown induced by the current pandemic, meeting this target in the given period of time seems unrealistic. Accordingly, the next section presents a projection for the probable achievement of the cumulative PV capacity, keeping in mind the past trend.

Projection of the Installed PV Capacity to Achieve the RE Capacity Expansion Target

The c-Si PV technology currently dominates the solar PV market, constituting 95% of the global market, while the share of thin amorphous technology remains minimal with limited information on its LCI [11]. This study, therefore, analyzes the share of the proposed capacity expansion based on c-Si PV technology only. In the absence of market share information of solar PV technologies in the Indian context, the study uses the global market share as a proxy for the Indian solar market. Accordingly, the projection is made for 95 GW of c-Si PV module capacity expansion,

Fig. 1 Annual and cumulative solar installations of rooftop PV and ground-mounted PV systems 2009–20 (in GW). Source: [40–45]

Table 1 Total solar installations commissioned and to be achieved by 2022 (in GW). Source: [40–45] and Authors' calculation

Sr. no.	PV system	Installations (in GW) (as of Dec. 2020)	Target (in GW)	Balance to be achieved (in GW)	Balance to be achieved (in %)
1.	Rooftop PV	5.3	40	34.7	86.7%
2.	Utility-scale ground-mounted PV	33.0	60	27.0	45%
	Total installations	38.4	100	61.7	61.7%

corresponding to 95% of the proposed 100 GW solar capacity expansion to be achieved by 2022. The projection of installed capacity is made using the E3-India model, an impact assessment tool developed from the internationally recognized E3ME global model framework.

The model is used to simulate the effects of economic and energy policies in India. Based on the Keynes-Leontief-Klein framework, the model is designed to provide policymakers a multidimensional policy impact analysis to assess the merits of a policy from the Economy-Energy-Environment standpoint. The feedback mechanism between these three dimensions is shown in Figure 2.

The economy module of the E3-India model provides the measure of economic activity and general price levels to the energy module. The energy module is constructed for each of the 21 energy users, disaggregated by five energy carrier for each region (see Table 11 in the Appendix). Based on the power generation technology and disaggregated energy user data, CO₂ emissions are estimated in the environment (emissions) module.

Given the importance of data quality for econometric models, E3-India model's database has been compiled with substantial effort. The baseline or the Business as Usual (BAU) scenario has been constructed by an extrapolation of previous sectoral growth rates compiled in the E3-India model's database. The model further adopts a method of calibration for scaling the forecasted values such that the model baseline is consistent with the constructed baseline.

Fig. 2 E3-India model structure. Source: [46]

The projected timeframe for the completion of the intended solar PV capacity target, along with the annual capacity addition, as suggested by the BAU baseline of the E3-India model, is presented in Figure 3. For 2029, only the net capacity addition required to meet the 95 GW target is shown.

Figure 3 indicates that the proposed installation of 95 GW of c-Si PV modules will be achieved by 2029. This is an important result, highlighting the large degree of variation in the year of completion of solar installations vis-à-vis the official target year of 2022. The break-up of the forecasted yearly installations according to the PV system (Rooftop and Ground-mounted PV) and PV technology (m-Si and p-Si) is presented in Table 12 in the Appendix. For this purpose, the share of m-Si and p-Si PV technologies in the c-Si solar PV market in India is assumed to be at par with their global share, i.e., 69.37% and 30.63% [11].

With a reliable timeframe for the achievement of the 95 GW capacity target, the next section lays out the goal and scope definition for performing a LCA of the intended solar capacity expansion.

LCA Goal and Scope Definition

This study deals with the attributional and comparative LCA of the 95 GW c-Si solar capacity expansion in India. The attributional LCA is conducted to measure the direct energy and environmental impact of the capacity expansion for ground-mounted PV and rooftop PV systems throughout its lifetime, and the comparative LCA is conducted to compare this impact across m-Si and p-Si PV technologies.

For this analysis, the total effective area of a 1 kW m-Si or p-Si PV system is assumed to be 10m² [35, 47]. Some of the harmonized characteristics defined for the purpose of this analysis are given below.

- Solar irradiation – the amount of energy received from the sun per unit area of solar PV panel is assumed to be 1700 kWh/m²/year in India [48]
- Performance ratio – the ratio of the actual electrical energy generated by PV plant to the theoretically possible electrical energy generated by the PV plant is assumed to be 0.75 in India [20]
- Module efficiency – the percentage of sunlight on the panel that is converted into electricity is assumed to be 14% for m-Si and 13.2% for p-Si PV technology in India [49]

Fig. 3 Forecasted solar PV capacity installation (in GW). Source: E3-India model. Note: for 2029, only the net capacity addition required to meet the 95 GW target is shown

- iv. Lifetime – the c-Si-based technology used in m-Si and p-Si technologies are assumed to have a life time of 30 and 25 years, respectively [50, 51]

The phases considered for the analysis range from resource extraction until EoL treatment, whereby the energy and environmental assessment of the production, construction, and operational phases is explained using LCA indicators such as Energy Pay Back Time (EPBT), Energy Return on Investment (EROI), and GHG Emission Rate, while the EoL assessment is done using the Full Recovery End-of-Life Photovoltaic (FREL P) method to incorporate the circular economy approach. The distinction also arises due to the variability in the functional unit reported in the literature for the respective phases, where the energy requirement for EoL is measured in per tonnage rather than in per m² terms, as is the case for the first three phases.

Life Cycle Inventory

The LCI step entails data collection and compilation for inputs (such as energy requirement and raw materials), intermediate processes, and outputs (such as GHG emissions and solid/liquid waste) for all the phases included in the study. This study takes into account energy and emission flows over four distinct phases in the process of electricity generation by means of photovoltaic panels. These include the production, construction, operation, and EoL phases, discussed in the following sections. The per-unit energy requirement (embodied energy) as inputs across the first three phases has been compiled for m-Si and p-Si PV technology with respect to the Ground-mounted PV and Rooftop PV systems, and is summarized in Table 2. For the national level analysis, the LCI has been compiled from the latest secondary sources available with sufficient geographical and technical correlation. The reason behind this approximation is the paucity of data due to the absence of macro-level LCA of solar PV in the Indian context. Thus, in order to undertake this novel analysis, the study has to rely on the more comprehensively documented European solar PV LCA studies for preparing the LCI. The LCI for the EoL phase is collated using the FREL P method. The recovered materials from PV waste at the EoL phase are quantified to measure the circular economy prospects in terms of the potential savings in energy and GHG emissions in the forthcoming production phase by substituting virgin materials with recovered materials.

Accordingly, the system boundaries of this study is schematised in Figure 4, consisting of the four phases of the 95 GW c-Si solar PV systems, based on the Circular Economy approach.

Production Phase

In this stage, the silicon feedstock is procured as raw material which then goes through a series of scientific procedures [18, 34]: First, the metallurgical-grade silicon (MG-Si) is prepared by carbothermic reduction of silicon-oxide (SiO₂) or silica from quartz sand. Second, the electronic grade-silicon (EG-Si) is produced from MG-Si which is a highly purified version and will be used in silicon wafers. Third, for m-Si PV, the EG-Si undergoes the highly energy-intensive Czochralski Process (Cz process) which operates at temperatures of 1100–1200°C and crystallizes the silicon to form a single crystal ingot of silicon. On the other hand, the p-Si PV does not require Cz process, hence, its energy requirement is always lower than m-Si PV. Next, the cell fabrication undergoes high-temperature diffusion, oxidation, and deposition after which the solar cells are interconnected with copper ribbon, encapsulated layer, and assembling of aluminum frame and tempered glass to form a PV module. The stepwise procedure for this phase is shown in Figure 5.

Table 2 Phase-wise embodied energy ground-mounted and rooftop m-Si and p-Si PV modules. Source: [35, 49, 52]

Sr. no.	Stages	Ground-mounted PV (kWh/m ²)		Rooftop PV (kWh/m ²)	
		m-Si	p-Si	m-Si	p-Si
1.	Production phase	1083	836	1083	836
1.1	Silicon feedstock	342	340	342	340
1.2	Czochralski process	399	0	399	0
1.3	Wafer process	85	183	85	183
1.4	Cell production	86	94	86	94
1.5	Module assembly	171	219	171	219
2.	Construction phase	533	533	233	233
2.1	Foundation and support structure	500	500	200	200
2.2	Inverter	33	33	33	33
3.	Operational phase	155	155	125	125
3.1	Over all operation and maintenance, electronic components, cables, and miscellaneous, etc.	155	155	125	125
	Total	1771	1524	1441	1194

The transformation of metallic silicon into solar silicon and the panel assembling is considered as the most energy-intensive steps in the manufacturing of solar panels due to the great electricity consumption in the former (even when the most efficient conversion technology is considered) and the use of highly energy-intensive materials like aluminum frame and glass roofing in the latter [22]. However, since LCA study on solar PV is minimal in the Indian context, the embodied energy LCI is not available for PV module manufacturing in India. Thus, this study relies on data collected from European studies. The embodied energy requirement for this entire phase is reported as 1083 kWh/m² for m-Si PV and 836 kWh/m² for p-Si PV module manufacturing

Fig. 4 System boundaries of the LCA study Source: Designed by Authors

Fig. 5 Stages of mono-crystalline and poly-crystalline silicon module manufacturing. Source: Designed by Authors

[49, 52]. As the European nations are technologically more advanced than India, the values reported by these studies can serve as the minimum thresholds in the Indian context.

Construction Phase

The ground-mounted PV, which is installed in large open areas, has higher levels of sophistication per kW of PV panel compared to rooftop PV construction, owing to factors such as preparation of foundation, land leveling, and fencing. Thus, the energy requirement in general will be higher for ground-mounted PV compared to rooftop PV. In the absence of national level estimates of embodied energy requirement for this phase, the study relies on the estimates proposed by a sub-national LCA which reported the respective values to be approximately 533 kWh/m² and 233 kWh/m² for ground-mounted and rooftop PV systems, respectively [34]. Since the main difference between m-Si and p-Si PV systems lies in the cell fabrication, the embodied energy for these two technologies is assumed to be the same across construction and operation phases.

Operational Phase

The operational phase constitutes cleaning of panels, repair, or replacement of any electronic/electrical component throughout the PV system's life-cycle. Here again, due to the larger scale of installation and supporting structures for ground-mounted PV, it has higher embodied energy requirements compared to rooftop PV. The embodied energy estimates for this stage are also based on the sub-national LCA discussed in the construction phase. For this phase, the respective energy requirement was reported as 155 kWh/m² and 125 kWh/m² for ground-mounted and rooftop systems, respectively [35].

The per-unit phase-wise embodied energy requirement is summarized in Table 2.

End-of-Life Phase—Circular Economy Approach

The EoL treatment of solar PV waste varies by the technology used. While clear differences have been highlighted between the EoL treatment of c-Si and thin-film amorphous panels, not much distinction has been made between the energy requirement for recycling of m-Si and p-Si PV modules [53, 54]. Thus, this paper evaluates the EoL treatment of c-Si technology PV waste for m-Si and p-Si PV modules combined.

As of now, India does not have any regulations for EoL recycling treatment designed specifically for PV waste. In fact, it is only the European Union which has a legislative framework in place for the recycling and disposal of PV waste materials as part of the producers' responsibility [55]. The EU solar industry has also established "PV CYCLE," an initiative to study innovative business models to undertake PV recycling systems more efficiently. The Full Recovery End-of-Life Photovoltaic (FREL P) method, prepared by an Italian PV Waste recycling company, SASIL S.p.A, in collaboration with PV CYCLE is considered to be the most advanced PV recycling system till date, expected to decrease lifetime environmental impact by 10–15% compared to other recycling methods [53]. The EoL treatment of PV waste using FREL P method is broadly covered in fifteen steps, demonstrated in Figure 6.

The FREL P method indicates that the embodied energy requirement for the entire EoL treatment of c-Si PV modules is 113.55 kWh/tonne of PV waste. The standard composition of a c-Si PV panel (per tonne) and the amount of materials that can be recovered from the same, as suggested by the FREL P method, is presented in Tables 13 and 14 in the Appendix. These tables reveal that 88.5% of the total materials in a PV module is composed of aluminum and glass, with almost 98% of both being recoverable.

Furthermore, the net monetary cost of PV recycling or EoL treatment using the FREL P method can be estimated as the difference between the total cost incurred during recycling, transportation, and disposal and the benefit gained from the materials and energy recovered during the process. The total cost can further be divided into private costs (investment, processing, and transportation fuel costs) and external costs (air, water, and land pollution) [54]. The total cost breakdown of the FREL P method is presented in Table 15 in the Appendix. The table indicates that a net benefit of USD 1.19/m² is registered from PV recycling, even after the external costs are considered [54].

Fig. 6 Steps in c-Si PV module waste treatment based on FRELPH. Source: Designed by Authors

Life Cycle Impact Assessment

Energy and Environmental Implications Using Attributional and Comparative LCA

The energy and environmental indicators reported in this section are with reference to the production, construction, and operational phases. The end-of-life or decommissioning phase is analyzed separately in the next section due to disparity in the documentation of data as the energy requirement for the end-of-life phase is available in tonnes of PV waste while the energy requirement for the first three lifecycle phases, namely, production, construction, and operation phases, is reported in kWh/m^2 of PV modules.

The parameters presented in this section include the Energy Pay Back Time (EPBT), energy return on energy investment (EROI), and GHG emission rate.

Energy Pay Back Time (EPBT)

EPBT is defined as the time required for the solar PV system to generate the same amount of energy used in its entire life cycle. The formula for calculating the same is given by Eq. 1.

$$EPBT \text{ (years)} = \frac{CED}{(E_{agen}/\eta_G) - E_{O\&M}} \quad (1)$$

Source: [56]

Where, i) CED: Cumulative Energy Demand of a PV system, calculated as a sum of the embodied energy starting from raw materials extraction up to construction, and the decommissioning phase. Excluding the decommissioning phase due to the disparity in data units, the CED will comprise of the embodied energy in the production and construction phase only.

ii) E_{agen} : Annual electricity generation, given by Eq. 2

$$E_{agen} = \text{irradiation} \times \text{performance ratio} \times \text{module efficiency} \quad (2)$$

Source: [56]

iii) $E_{O\&M}$: Embodied Energy for Operational Phase

iv) η_G : Conversion efficiency, i.e., the average life-cycle primary energy to electricity conversion at the demand side. It is assumed to be 20% [57].

Based on the embodied energy inventory presented in Table 2, the EPBT for m-Si and p-Si PV technologies for ground-mounted PV and rooftop PV is presented in Table 3.

Energy Return on Investment (EROI)

EROI is defined as the ratio of the usable energy returned during a system's operating life, to all the energy needed to make this energy usable. Higher EROI implies higher efficiency in terms of producing economically useful energy output. Moreover, as a dimensionless ratio, EROI can be used for analyzing and comparing different types of technologies [58]. Thus, EROI helps to evaluate the long-term viability of a PV system by looking at the overall energy performance over its entire lifetime [47]. It can be calculated using Eq. 3.

$$EROI = \frac{\text{lifetime}}{EPBT} \quad (3)$$

Source: [49]

The resulting EROI are presented in Table 4.

Table 3 EPBT for ground-mounted and rooftop PV system for different PV technologies. Source: Authors' calculations

Sr. no.	PV system	PV technology	EPBT (in years)
1.	Ground-mounted PV	m-Si	2.2
		p-Si	2.0
2.	Rooftop PV	m-Si	1.7
		p-Si	1.5

Table 4 Energy Return On Investment for ground-mounted PV and rooftop PV system for different PV technologies. Source: Authors' calculations

Sr. no.	PV system	PV technology	EROI
1.	Ground-mounted PV	m-Si	13.7
		p-Si	12.5
2.	Rooftop PV	m-Si	17.5
		p-Si	16.8

GHG Emission Rate

The GHG emissions rate is a useful index for evaluating the effectiveness of a PV system in the context of global warming. This can be calculated by determining the total GHG emissions during a life cycle divided by the total amount of annual power generation over its lifetime, as presented in Eq. 4 [18].

$$\text{GHG emission rate} \left(\frac{\text{gCO}_2}{\text{kWh}} \right) = \frac{\text{Total GHG emission during life cycle}}{E_{\text{agen}} \times \text{Lifetime}} \quad (4)$$

Source: [18]

Where total GHG emission during lifecycle can be calculated on the basis of lifetime embodied energy, presented in Table 2. Assuming that the embodied energy throughout the life-cycle of solar PV will be met from coal-fired thermal power plants (TPPs), the total GHG emissions generated throughout the life-time of the m-Si and p-Si PV systems can be calculated using Eq. 5.

$$\begin{aligned} \text{Total GHG emissions during lifecycle} &= \text{Lifecycle Embodied energy} \\ &\times \text{Avg CO}_2\text{eq intensity for electricity generation from coal} \end{aligned} \quad (5)$$

The electricity generation from coal-based TPPs in India leads to an average GHG emission of 0.957 kgCO₂/kWh [59].

Replacing Eq. 5 in Eq. 4, the GHG emission rate across PV technology and PV systems can be found. The result for the same is presented in Table 5.

Cumulative Energy and Environmental Burden

Based on the LCI for embodied energy presented in Table 2, the phase-wise lifetime embodied energy of 95 GW capacity of m-Si and p-Si modules for ground-mounted PV and rooftop PV can be calculated. For this purpose, the unit of measurement was converted from kWh/m² to kWh/

Table 5 GHG emission rate for ground-mounted PV and rooftop PV system for different PV technologies. Source: Authors' calculations

Sr. no.	PV system	PV technology	GHG emission rate (gCO ₂ /kWh)
1.	Ground-mounted PV	m-Si	316.5
		p-Si	346.6
2.	Rooftop PV	m-Si	257.5
		p-Si	271.5

10m² to measure the energy flows per kW of solar PV capacity. This was then used to calculate the embodied energy for 95 GW solar capacity and the results are presented in Table 6.

Based on the cumulative embodied energy, the total GHG emission during lifecycle for 95 GW capacity can be calculated using Eq. 5. The results for the phase-wise lifetime GHG emissions from 95 GW m-Si and p-Si solar PV modules are presented in Table 7.

The cumulative embodied energy and GHG emissions are calculated on an annual basis as well, based on the yearly installations presented in Table 12 in the appendix. The result for the same is presented in Table 16 in the Appendix. The annual GHG emissions have been calculated using Eq. 6.

Annual GHG emissions

$$= \frac{\text{Embodied energy} \times \text{Avg CO}_2\text{eq intensity for electricity generation from coal}}{\text{Lifetime of PV System}} \quad (6)$$

Source: [35]

Having evaluated the energy and environmental implications during the first three phases of solar PV in this section, the next section evaluates the prospects of the circular economy approach in the EoL phase.

FRELP Analysis for End-of-Life Phase

The 95 GW worth of c-Si PV modules will generate approximately 6,576 tonnes of waste at its EoL². However, the total 6,576 tonnes of PV waste will not be generated all at once. With a life time of 30 and 25 years for m-Si and p-Si modules, respectively, PV waste will start accumulating annually once the solar modules reach the end of their life time. This timeframe ranges between 2034 and 2059 for the 95 GW capacity installed until 2029. Figure 7 presents the annual and cumulative waste generation which is expected to accumulate from 2034 onward. The annual PV-waste generation segregated by PV system and technology is presented in Table 17 in the appendix.

Based on the composition of one tonne of PV waste presented by Latunussa et al. [53] (see Table 13 in the appendix), the material-wise composition of the 6,576 tonnes PV waste is calculated and presented in Table 8.

Using the material recovery information from the FRELP method presented in Table 14 in the appendix, the expected material recovered from 95 GW or 6,576 tonnes of PV waste is shown in Table 9.

As per the FRELP method, approximately 90.7% of PV materials can be recovered from 6,576 tonnes of PV waste with the process entailing electricity consumption and GHG emissions of 678.6 MWh and 648 tonnes of CO₂ eq., respectively.

With the help of the cost benefit analysis presented by Markert, Celik & Apul (2020) (see Table 15 in the appendix), the total private and external costs of recycling 95 GW of c-Si PV waste and the commercial value of recovered materials (aluminum, glass, silver, silicon, and copper) are calculated and presented in Table 10. Private costs include the cost of investment, processing, transportation, and disposal while the external costs are from Cumulative Energy Demand, Global Warming potential, acidification, freshwater toxicity, particulate matter, etc.

Thus, the EoL treatment of 95 GW c-Si modules will entail a net loss of USD 65 million.

² 1 GW of solar PV modules weighs approximately 69.2 tonnes [38]

Table 6 Phase-wise life time embodied energy for 95 GW ground-mounted and rooftop m-Si and p-Si PV modules (in GWh). Source: Authors' calculations

Sr. no.	Stages	Ground-mounted PV		Rooftop PV	
		m-Si	p-Si	m-Si	p-Si
1.	Production phase	428868	145464	285912	96976
2.	Construction phase	211068	92742	61512	27028
3.	Operational phase	61380	26970	33000	14500
	Total	701316	265176	380424	138504

Discussion

The study reports the energy requirement levels of a crystalline-silicon PV module to range from 1194–1771 kWh/m², varying by the PV technology and mode of installation, which is in line with the broad range of crystalline-silicon PV module energy requirement levels of 150–1845 kWh/m² reported in the literature [19]. The study also finds the more efficient monocrystalline PV modules to be more energy and emission intensive with higher EPBT than polycrystalline PV modules for each mode of installation, a finding that has been extensively documented in the past [18]. Moreover, the study adds to the literature through two novel findings. First, by distinguishing the PV technology by mode of installation, the study finds that ground-mounted polycrystalline PV systems are more energy and emission-intensive than rooftop monocrystalline PV systems, as indicated by the higher EPBT of the former. The mode of installation, therefore, becomes an important factor influencing the environmental performance of the two PV technologies as ground-mounted PV systems entail higher energy requirement. Second, the study finds that the advantage that polycrystalline PV systems have over monocrystalline PV systems in terms of environmental performance vanishes when the lower lifetime of the former is accounted for along with its lower efficiency. This is shown by the lower EROI and higher GHG emission rate of polycrystalline PV systems for each mode of installation. Thus, the lower efficiency of polycrystalline PV technology does not hurt its environmental performance as much as its lower lifetime. Given that GHG emission is inversely proportional to the lifetime [18], increasing polycrystalline lifetime from 25 to 30 years can reduce its GHG emission rate from 346.6 gCO₂eq/kWh to 288.9 gCO₂eq/kWh for ground-mounted systems and from 271.5 gCO₂eq/kWh to 226.3 gCO₂eq/kWh for rooftop systems, at the same module efficiency of 13.2%. This will also make polycrystalline PV systems regain its competitive edge over monocrystalline PV systems in terms of environmental performance. Similarly, assuming a lifetime of 30 years for both monocrystalline and polycrystalline PV modules, Yue et al. [49] report the EROI for the later

Table 7 Phase-wise GHG emissions from 95 GW ground-mounted and rooftop m-Si and p-Si PV modules (in million kgCO₂e). Source: Authors' calculations

Sr. no.	Stages	Ground-mounted PV		Rooftop PV	
		m-Si	p-Si	m-Si	p-Si
1.	Production phase	410.4	139.2	273.6	92.8
2.	Construction phase	202.0	88.8	58.9	25.9
3.	Operational phase	58.7	25.8	31.6	13.9
	Total	671.2	253.8	364.1	132.5

Fig. 7 Annual and cumulative PV waste accumulation under BAU scenario (in tonnes). Source: Authors' calculations

to be higher than that of the former. However, by accounting for the shorter lifetime of polycrystalline PV technology, the study demonstrates the impact of lifetime of a PV system on its long-term environmental viability.

In terms of phase-wise energy and emission intensity, the production phase accounts for 55–75% of the total embodied energy requirement and GHG emissions, depending on the PV technology and mode of installation. This can be attributed to massive electricity consumption in transforming metallic silicon into solar silicon and the use of highly energy-intensive materials like aluminum and glass in panel assembling [22]. The most effective way, therefore, to improve the modules' environmental performance is to reduce the energy input in the manufacturing phase of the modules, provided other parameters remain constant [21]. For this reason, incorporating the circular economy approach in the solar PV lifecycle becomes inevitable. With the help of FRELP analysis, the study finds that 90.7% of the PV waste resulting from 95 GW worth of solar PV systems can be recovered at EoL. This includes a substantial portion of the most energy-intensive components of a solar PV module, aluminum, and glass. In terms of the proportion of PV waste that can be recovered at EoL,

Table 8 Crystalline-silicon-based PV panel composition for solar PV system of 95 GW. Source: [53] and Authors' calculations

Sr. no.	Materials	Quantity (in tonnes)
1.	Glass	4,603
2.	Aluminum frame	1,184
3.	Copper connector	66
4.	Polymer-based adhesive (EVA) encapsulation layer (from cables)	335
5.	Back-sheet layer (based on polyvinyl fluoride)	99
6.	Silicon metal solar cell	240
7.	Silver	3
8.	Aluminum, internal conductor	35
9.	Copper, internal conductor	7
10.	Various metal (tin, lead)	3
	Total	6,576

Table 9 Materials recovered and energy saved from recycling 6,576 tonnes of PV waste. Source: [53] and Authors' calculations

Sr. no.	Primary materials recovered	Quantity (in tonnes)	% of recovered material
1.	Primary aluminum	1,196.9	98.0%
2.	Raw materials for the production of primary white glass for packaging	4,511.2	98.6%
3.	Primary copper	28.8	43.8%
4.	Primary metallurgical-grade silicon metals (MG-Si)	228.1	95.0%
5.	Primary silver	3.3	94.3%
		Energy content (in MWh)	
6.	Produced by the incineration of PV encapsulation, back-sheet layer, and polymers	Electricity production 454.5 Thermal Energy 918.5	

this study provides an update to the proportion reported by Gautam et al. [34], which estimates only 70% of the PV waste to be recoverable. Furthermore, going beyond the economic savings reported by Gautam et al. [34], the present study incorporates the corresponding energy and emission savings from the recovery of raw materials at EoL. The amount of aluminum and glass recovered at the EoL, as shown in Table 9, will lead to a direct saving of 51.53 GWh and 18.8 GWh of energy, respectively. Correspondingly, the savings in CO₂ emissions will amount to 9.8 tonnes CO₂ and 3.8 tonnes CO₂, respectively³.

The cost-benefit analysis of the EoL treatment presented in the study reports a loss of USD 65 million. However, when viewed as a proportion of the total cost, this loss amounts to less than 1%. On the other hand, the cost of purchasing virgin raw materials is nearly seven times the cost of recovering them through recycling [54]. The significant difference between the costs can be attributed to the energy and cost-intensive extraction of raw materials that their recovery does not entail. For instance, 94.3% of the most expensive component of a PV module, silver, is recoverable through EoL treatment. Prioritizing its recovery can bring down the private and external cost of PV module manufacturing substantially. Similar is the case of silicon, which has a recovery rate of 95%. Thus, despite the loss, recycling of the PV waste is a more economical option vis-à-vis manufacturing virgin material. However, the upfront loss is bound to discourage manufacturers from opting for EoL treatment. In such a situation, the onus is on the government to undertake subsidization of EoL treatment to make it financially feasible. While the Government of India has allocated 30% of the project cost as subsidy with an intention of promoting investment in domestic solar equipment manufacturing to counter cheaper imports from China [60], no fiscal incentive has been provided for the downstream processes. A forward-looking strategy, however, requires immediate attention to be directed toward enabling EoL treatment to manage the impending PV waste accumulation, which will be generated irrespective of whether manufacturing is indigenised or not. A subsidy would in effect reduce the private cost of recycling by an equal amount. Thus, a breakeven point is to equate the subsidy to the loss i.e. USD 65 million. However, the entire PV waste evaluated in the study will not be treated at once, so an equivalent amount would be equal to USD 690/MW.

³ The embodied energy associated with manufacturing virgin aluminum and glass is 155 MJ/kg and 15 MJ/kg, respectively. The corresponding value for embodied carbon is 8.24 kgCO₂/kg and 0.85 kgCO₂/kg, respectively [62].

Moreover, incentivizing investment in EoL treatment will require a profit margin for the investors. Therefore, this break-even amount is the minimum threshold and the point of reference that the government should look at while deciding the extent of the subsidy. Another way to highlight the positive environmental impact of the EoL treatment is to look at the potential capacity that can be installed from the economic value of the recovered materials. The study finds that the economic value of recovered materials from 95 GW c-Si PV waste is approximately equal to USD 11.74 billion as shown in Table 10. With an installation cost of USD 618/kW in India which is currently the lowest in the world [61], approximately 19 GW of solar capacity can be installed from the economic value of the recovered materials.

Conclusion

In an attempt to achieve the twin objectives of energy security and energy sustainability, India has undertaken the world's largest RE capacity expansion program of which solar energy is the largest component. The target is to achieve 100 GW of installed solar capacity by 2022. With nearly 40% of the target achieved so far, meeting the target by 2022 seems unlikely. To address the uncertainty about the probable achievement of the target, the study presents a timeframe for the same, according to which the target is likely to be achieved by 2029. In stating so, the study counters the projections provided by Gautam et al. [34], which estimates the installed solar capacity to reach 347.5 GW by 2030. However, given that the study does not take into account the slowdown induced by the COVID-19 pandemic and its anticipated prolonged impact, this projection seems highly ambitious. Furthermore, the study undertakes the attributional and comparative LCA to evaluate the energy and environmental impact of solar PV installation using m-Si and p-Si PV technologies in India and reports its findings through indicators such as EPBT, EROI, and GHG emission rate. The study relies on comprehensively documented European data sources since, to the best knowledge of the authors, the macro-level solar PV LCA studies have not been conducted thus far in the Indian context. The results highlight an important finding: the extant literature claiming the superiority of polycrystalline PV technology over monocrystalline technology in terms of environmental performance needs to be assessed critically in the context of the mode of installation and difference in lifetime.

Next, the study projects the amount of PV waste that will accumulate at the end-of-life time from the capacity expansion, expected to accumulate 2034 onward. By incorporating an in-depth analysis of the end-of-life phase using the FRELP method to understand the circular economy prospects of the Indian Solar Industry, this study provides a novel extension to existing LCA studies, unparalleled in literature. Results indicate that the energy recovery from PV waste

Table 10 Cost benefit analysis of 95 GW c-Si technology PV waste. Source: [54] and Authors' calculations

Sr. no.	Particulars	Value (USD billion)
1.	Private costs ^a	6.38
2.	External costs ^b	5.42
3.	Commercial/economic value of recovered materials ^c	11.74
4.	Net benefit (Sr. no. 3 - 1 - 2)	-0.065

Note: ^a private costs include the cost of investment, processing, transportation and disposal; ^b external costs are from Cumulative Energy Demand, Global Warming potential, acidification, freshwater toxicity, particulate matter, etc.; ^c aluminum, glass, silver, silicon, and copper

recycling is tremendous which will remain unutilized if such downstream operations are not prioritized. Moreover, the reuse of recovered aluminum, glass, silver, and silicon in the manufacture of PV modules can be significantly beneficial not only from the energy-environment standpoint but also from the economic perspective as the economic value of the recovered material can help in installing approximately 19 GW of additional solar capacity. At the same time, there are some materials such as lead and tin which cannot be recovered and are disposed of as solid/liquid waste at the end-of-life time. Thus, responsible handling of PV waste is crucial to minimize the harmful impact on the environment as well as on human health. This in turn requires a comprehensive legislative framework, currently missing in India. Furthermore, there is no accountability or delineation of responsibilities among the producer or governmental institutions for PV waste recycling which can further delay the process. In this direction, the study presents a cost-benefit analysis of the end-of-life treatment of the cumulative PV waste to inform the policymakers of the likely cost to be incurred. The results indicate a net loss of USD 65 million from the process, however, when evaluated in context of the energy and environmental benefits and compared with the cost of virgin materials, recycling turns out to be the preferred option. In order to make this financially feasible, it is suggested that the government considers subsidization of the end-of-life treatment of PV waste. No loss-no gain scenario would require a subsidy of USD 690/MW, however, keeping the incentive for investors in mind, the study suggests that the actual subsidy should be greater than this break-even value. Determining the optimal amount of this subsidy can be a subject for future research. Meanwhile, by presenting a national energy and environment framework constituting LCA and circular economy approach for the c-Si PV modules, this study intends to serve as a reference for future studies with focus on policy implications.

A possible limitation of the study lies in the exclusion of the energy and environmental burden of manufacturing of selected raw materials⁴ from the raw material acquisition phase of the LCA. Inclusion of this aspect will result in higher energy and environmental burden than reported in this study. A precise estimate of the extent of this impact is a potential avenue for future research. Another opportunity for future research lies in extending the current study by conducting a consequential LCA of solar PV installation using the input-output approach.

Funding The authors did not receive support from any organization for the submitted work.

Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Competing Interests The authors declare no competing interests.

⁴ Due to paucity of data for embodied energy and embodied carbon for copper, aluminum, glass, and silver, their energy and environmental burden could not be added in the raw material acquisition phase of the LCA. However, the same has been included for silicon, which alone makes production the most energy and emission intensive phase of solar PV LCA.

Appendix

Table 11 E3-India energy classifications

Fuel users	Fuels	Power technologies
1 Power own use and trans.	1 Coal	1 Nuclear
2 Other energy own use and transformation	2 Oil	2 Oil
3 Basic metal	3 Natural gas	3 Coal
4 Metal goods	4 Electricity	4 Coal + CCS
5 Chemicals	5 Biomass	5 IGCC
6 Non-metallic minerals		6 IGCC + CCS
7 Food, drink, and tobacco		7 CCGT
8 Textile, leather, and clothing		8 CCGT + CCS
9 Rubber and plastics		9 Solid biomass
10 Paper and publishing		10 S biomass CCS
11 Engineering etc.		11 BIGCC
12 Other industry		12 BIGCC + CCS
13 Construction		13 Biogas
14 Rail transport		14 Biogas + CCS
15 Road transport		15 Tidal
16 Air transport		16 Large hydro
17 Water transport		17 Onshore
18 Households		18 Offshore
19 Services		19 Solar PV
20 Agriculture and fishing		20 CSP
21 Non-energy use		21 Geothermal
		22 Wave
		23 Fuel cells
		24 CHP

Source: [44]

Table 12 Business-as-usual scenario

Sr. no.	Year	Monocrystalline PV		Polycrystalline PV		Cumulative installation
		Rooftop PV	Ground-mounted	Rooftop PV	Ground-mounted	
1	2009	0.0	4.0	0.0	1.7	5.7
2	2010	0.0	7.9	0.0	3.5	17.1
3	2011	14.5	99.0	6.4	43.5	180.5
4	2012	19.8	638.9	8.7	280.7	1128.6
5	2013	62.0	627.0	27.3	275.5	2120.4
6	2014	67.3	582.8	29.6	256.1	3056.2
7	2015	118.8	1407.8	52.2	618.6	5253.5
8	2016	289.1	2557.5	127.0	1123.8	9350.9
9	2017	656.7	5698.4	288.6	2503.9	18498.4
10	2018	1092.3	4410.8	480.0	1938.1	26419.5
11	2019	728.6	4119.7	320.2	1810.2	33398.2
12	2020	474.5	1663.2	208.5	730.8	36475.3
13	2021 (F)	1094.1	1641.1	480.7	721.1	40412.2
14	2022 (F)	1496.6	2244.8	657.6	986.4	45797.6
15	2023 (F)	1732.0	2598.0	761.0	1141.5	52030.2
16	2024 (F)	1727.6	2591.4	759.1	1138.6	58246.9
17	2025 (F)	2149.1	3223.7	944.3	1416.5	65980.5
18	2026 (F)	2282.0	3423.0	1002.7	1504.0	74192.2
19	2027 (F)	2373.2	2061.0	1042.8	905.6	80574.8
20.	2028 (F)	6355.2	0.0	2792.4	0.0	89722.5
21.	2029 (F)	3666.5	0.0	1611.0	0.0	95000.0

Table 13 Crystalline-silicon based PV panel composition (per tonne)

Sr. no.	Materials	Quantity (in kgs)	Share of total (in %)
1.	Glass	700	70.0
2.	Aluminum frame	180	18.0
3.	Copper connector	10	1.0
4.	Polymer-based adhesive (EVA) encapsulation layer (from cables)	51	5.1
5.	Back-sheet layer (based on polyvinyl fluoride)	15	1.5
6.	Silicon metal solar cell	36.5	3.7
7.	Silver	0.53	0.1
8.	Aluminum, internal conductor	5.3	0.5
9.	Copper, internal conductor	1.14	0.1
10.	Various metal (tin, lead)	0.53	0.1
	Total	1000	100

Source: [51]

Table 14 Materials recovered and energy saved annually in the recycling process (1 tonne PV waste)

Sr. no.	Primary materials recovered	Quantity	Unit	% of recovered material
1.	Primary aluminum	182	Kg	98.0%
2.	Raw materials for the production of primary white glass for packaging	686	Kg	98.6%
3.	Primary copper	4.38	Kg	43.8%
4.	Primary metallurgical-grade silicon metals (MG-Si)	34.68	Kg	95.0%
5.	Primary silver	0.50	Kg	94.3%
		Energy content/ kg		
6.	Produced by the incineration of PV encapsulation, back-sheet layer, and polymers	Electricity production Thermal energy	69.12 139.67	kWh kWh

Source: [52]

Table 15 Per unit cost benefit analysis of 1 kWh/m² c-Si PV module

Sr. no.	Particulars	Value (in USD)
1.	Private costs (transportation, landfilling/disposal, electricity consumed materials, etc.)	6.72
2.	External costs	5.71
3.	Commercial/economic value of recovered materials (aluminum, glass, silver, silicon, and copper)	13.62
4.	Net benefit (Sr. no. 3 – 1 - 2)	1.19

Source: [52]

Table 16 BAU scenario: annual embodied energy and CO₂ emissions from production, construction, and operational phases

Sr. no.	Year	m-Si technology			p-Si technology		
		Annual installation (in MW)	Embodied energy (in GWh)	GHG emissions (in thousand tonnes)	Annual installation (in MW)	Embodied energy (in GWh)	GHG emissions (in thousand tonnes)
1.	2009	4.0	70.1	2.2	1.7	26.5	1.0
2.	2010	7.9	140.3	4.5	3.5	53.0	2.0
3.	2011	113.5	1962.5	62.6	49.9	739.1	28.3
4.	2012	658.7	11599.9	370.0	289.4	4382.1	167.7
5.	2013	689.0	11998.2	382.7	302.8	4524.1	173.2
6.	2014	650.1	11291.1	360.2	285.7	4255.7	162.9
7.	2015	1526.6	26643.7	849.9	670.8	10050.3	384.7
8.	2016	2846.6	49459.0	1577.7	1250.8	18642.6	713.6
9.	2017	6355.1	110382.4	3521.2	2792.4	41604.1	1592.6
10.	2018	5503.1	93855.0	2994.0	2418.0	35266.8	1350.0
11.	2019	4848.4	83459.9	2662.4	2130.3	31409.9	1202.4
12.	2020	2137.7	36293.4	1157.8	939.3	13627.0	521.6
13.	2021	2735.2	44829.5	1430.1	1201.8	16729.3	640.4
(F)							
14.	2022	3741.4	61321.7	1956.2	1644.0	22883.8	876.0
(F)							
15.	2023	4330.0	70968.6	2263.9	1902.6	26483.8	1013.8
(F)							
16.	2024	4319.0	70788.0	2258.1	1897.7	26416.4	1011.2
(F)							
17.	2025	5372.9	88061.2	2809.2	2360.8	32862.4	1258.0
(F)							
18.	2026	5705.0	93504.5	2982.8	2506.7	34893.7	1335.7
(F)							
19.	2027	4434.2	70698.3	2255.3	1948.4	26251.9	1004.9
(F)							
20.	2028	6355.2	91578.5	2921.4	2792.4	33341.7	1276.3
(F)							
21.	2029	3666.5	52834.2	1685.4	1611.0	19235.8	736.3
(F)							

Source: Authors' calculation

References

1. Indiatat Database. (2020). Per capita consumption of electricity in India (1950 to 1956, 1957–1958 to 2019–2020). Retrieved from Indiatat. Socio-Economic Statistical Information about India: <https://www.indiatat.com/>
2. PIB. (2017). Vision of the government is '24x7 Power for All'. Retrieved from Press Information Bureau, Government of India: <https://pib.gov.in/PressReleaseDetail.aspx?PRID=1512041>
3. Tiewsoh LS, Jirasek J, Sivek M (2019) Electricity generation in India: present state, future outlook and policy implications. *Energies* 12(7). <https://doi.org/10.3390/en12071361>
4. Climate Action Tracker. (2020). Climate action tracker. Retrieved from Pledges and Targets: <https://climateactiontracker.org/countries/india/pledges-and-targets/>

Table 17 BAU scenario amount of waste generated for c-Si technology solar PV at the end-of-life time

Sr. no.	Year-end of lifetime	In MW		In tonnes		Glass	Aluminum	Copper	Polymer-based adhesive	Polyvinyl fluoride	Silicon	Silver	Various metals (tin, lead)
		Annual PV waste	Annual PV waste	Annual PV waste	Annual PV waste								
1.	2034	1.7	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.	2035	3.5	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.	2036	49.9	3.5	3.5	2.4	0.6	0.0	0.2	0.2	0.1	0.0	0.0	0.0
4.	2037	289.4	20.0	20.0	14.0	3.7	0.2	1.0	1.0	0.3	0.7	0.0	0.0
5.	2038	302.8	21.0	21.0	14.7	3.9	0.2	1.1	1.1	0.3	0.8	0.0	0.0
6.	2039	289.6	20.0	20.0	14.0	3.7	0.2	1.0	1.0	0.3	0.7	0.0	0.0
7.	2040	678.7	47.0	47.0	32.9	8.7	0.5	2.4	2.4	0.7	1.7	0.0	0.0
8.	2041	1364.3	94.4	94.4	66.1	17.5	1.1	4.8	4.8	1.4	3.4	0.1	0.1
9.	2042	3451.1	238.9	238.9	167.2	44.3	2.7	12.2	12.2	3.6	8.7	0.1	0.1
10.	2043	3107.1	215.1	215.1	150.6	39.9	2.4	11.0	11.0	3.2	7.9	0.1	0.1
11.	2044	2780.4	192.5	192.5	134.7	35.7	2.1	9.8	9.8	2.9	7.0	0.1	0.1
12.	2045	2465.9	170.7	170.7	119.5	31.6	1.9	8.7	8.7	2.6	6.2	0.1	0.1
13.	2046	4048.4	280.2	280.2	196.2	51.9	3.1	14.3	14.3	4.2	10.2	0.1	0.1
14.	2047	7999.1	553.7	553.7	387.6	102.6	6.2	28.2	28.2	8.3	20.2	0.3	0.3
15.	2048	7405.7	512.6	512.6	358.8	95.0	5.7	26.1	26.1	7.7	18.7	0.3	0.3
16.	2049	6746.1	467.0	467.0	326.9	86.5	5.2	23.8	23.8	7.0	17.0	0.2	0.2
17.	2050	4498.5	311.4	311.4	218.0	57.7	3.5	15.9	15.9	4.7	11.4	0.2	0.2
18.	2051	5241.9	362.9	362.9	254.0	67.2	4.0	18.5	18.5	5.4	13.2	0.2	0.2
19.	2052	5689.8	393.9	393.9	275.7	73.0	4.4	20.1	20.1	5.9	14.4	0.2	0.2
20.	2053	7122.4	493.0	493.0	345.1	91.4	5.5	25.1	25.1	7.4	18.0	0.3	0.3
21.	2054	5930.0	410.5	410.5	287.3	76.1	4.6	20.9	20.9	6.2	15.0	0.2	0.2
22.	2055	5372.9	371.9	371.9	260.3	68.9	4.1	19.0	19.0	5.6	13.6	0.2	0.2
23.	2056	5705.0	394.9	394.9	276.4	73.2	4.4	20.1	20.1	5.9	14.4	0.2	0.2
24.	2057	4434.2	306.9	306.9	214.9	56.9	3.4	15.7	15.7	4.6	11.2	0.2	0.2
25.	2058	6355.2	439.9	439.9	307.9	81.5	4.9	22.4	22.4	6.6	16.1	0.2	0.2
26.	2059	3666.5	253.8	253.8	177.7	47.0	2.8	12.9	12.9	3.8	9.3	0.1	0.1
27.	Total	95000.0	6576.1	6576.1	4603.3	1218.6	73.3	335.4	335.4	98.6	240.0	3.5	3.5

Source: Authors' calculation

5. PIB. (2015) Year end review - solar power target reset to one lakh MW. Retrieved from Press Information Bureau, Government of India: <https://pib.gov.in/newsite/PrintRelease.aspx?relid=133220>
6. Aayog NITI (2015) Report of the expert group on 175 GW RE by 2022. Niti Aayog, Government of India, New Delhi Retrieved from <https://niti.gov.in/writereaddata/files/175-GW-Renewable-Energy.pdf>
7. MNRE. (2021). Solar Energy. Retrieved from Ministry of New and Renewable Energy, Government of India: <https://mnre.gov.in/solar/current-status/>
8. IEA (2019) Global Energy & CO₂ Status Report. The latest trends in energy and emissions in 2018. International Energy Agency. Retrieved from https://iea.blob.core.windows.net/assets/23f9eb39-7493-4722-aced-61433cbffe10/Global_Energy_and_CO2_Status_Report_2018.pdf
9. Kabir E, Kumar P, Kumar S, Adelodun AA, Kim K-H (2018) Solar energy: potential and future prospects. *Renew Sust Energ Rev*:894–900. <https://doi.org/10.1016/j.rser.2017.09.094>
10. Environment Canada. (2014). Assessment of the environmental performance of solar photovoltaic technologies. Environment Canada and Canmet Energy. Retrieved from <http://pvinnovation.ca/wp-content/uploads/2014/03/Assessment-of-the-Environmental-Performance-of-Solar-Photovoltaic-Technologies-Environment-Canada-03.2014.pdf>
11. Fraunhofer ISE. (2020). Photovoltaics Report. Fraunhofer Institute of Solar Energy Systems, ISE. Retrieved from <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>
12. Solangi KH, Islam MR, Saidur R, Rahim NA, Fayaz H (2011) A review on global solar energy policy. *Renew Sust Energ Rev*:2149–2163. <https://doi.org/10.1016/j.rser.2011.01.007>
13. Breyer C, Koskinen O, Blechinger P (2015) Profitable climate change mitigation: the case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. *Renew Sust Energ Rev* 49:610–628. <https://doi.org/10.1016/j.rser.2015.04.061>
14. Adam DA, Apaydin G (2016) Grid connected solar photovoltaic system as a tool for green house gas emission reduction in Turkey. *Renew Sust Energ Rev* 53:1086–1091. <https://doi.org/10.1016/j.rser.2015.09.023>
14. Creutzig F, Agoston P, Goldschmidt JC, Luderer G, Nemet G, Pietzcker RC (2017) The underestimated potential of solar energy to mitigate climate change. *Nat Energy*. <https://doi.org/10.1038/nenergy.2017.140>
15. Shahsavari A, Akbari M (2018) Potential of solar energy in developing countries for reducing energy-related emissions. *Renew Sust Energ Rev* 90:275–291. <https://doi.org/10.1016/j.rser.2018.03.065>
16. Battisti R, Corrado A (2005) Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* 30:952–967. <https://doi.org/10.1016/j.energy.2004.07.011>
17. ISO. (2006) ISO 14044:2006(en) Environmental management - life cycle assessment - requirements and guidelines. Retrieved from International Organization for Standardization.: <https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en>
18. Ludin NA, Mustafa NI, Hanafiah MM, Ibrahim MA, Teridi MA, Sepeai S et al (2018) Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review. *Renew Sust Energ Rev* 96:11–28. <https://doi.org/10.1016/j.rser.2018.07.048>
19. Zhou ZV (2016) Meta-analysis of life cycle assessment studies on solar photovoltaic systems. *Clemson University TigerPrints* Retrieved from <https://core.ac.uk/download/pdf/268649775.pdf>
20. Hsu DD, O'Donoghue P, Fthenakis V, Heath GA, Kin HC, Sawyer P et al (2012) Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation. *J Ind Ecol* 16. <https://doi.org/10.1111/j.1530-9290.2011.00439.x>
21. Pacca S, Sivaraman D, Keoleian A (2007) Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy* 35:3316–3326. <https://doi.org/10.1016/j.enpol.2006.10.003>
22. Stopatto, A. (2008). Life cycle assessment of photovoltaic electricity generation. *Energy*, 224–232. <https://doi.org/10.1016/j.energy.2007.11.012>
23. Nugent D, Sovacool BK (2014) Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical metasurvey. *Energy Policy* 65:229–244. <https://doi.org/10.1016/j.enpol.2013.10.048>
24. Nikolau IE, Jones N, Stefanakis A (2021) Circular economy and sustainability: the past, the present and the future directions. *Circular Econ Sustain* 1:1–20. <https://doi.org/10.1007/s43615-021-00030-3>
25. Halog A, Anieke S (2021) A review of circular economy studies in developed countries and its potential adoption in developing countries. *Circular Econ Sustain* 1:209–230. <https://doi.org/10.1007/s43615-021-00017-0>
26. Kim H, Park H (2018) PV waste management at the crossroads of circular economy and energy transition: the case of South Korea. *Sustainability* 10. <https://doi.org/10.3390/su10103565>
27. Kim B, Azzaro-Pantel C, Pietrzak-David M, Maussion P (2019) Life cycle assessment for a solar energy system based on reuse components for developing countries. *J Clean Prod*:1459–1468. <https://doi.org/10.1016/j.jclepro.2018.10.169>

28. Paiano A (2015) Photovoltaic waste assessment in Italy. *Renew Sust Energ Rev*. <https://doi.org/10.1016/j.rser.2014.07.208>
29. Santos JD, Alonso-Garcia MC (2018) Projection of the photovoltaic waste in Spain until 2050. *J Clean Prod*:1613–1628. <https://doi.org/10.1016/j.jclepro.2018.05.252>
30. Heath GA, Silverman TJ, Kelmpe M, Deceglie M, Ravikumar D, Remo T et al (2020) Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nat Energy* 5:502–510. <https://doi.org/10.1038/s41560-020-0645-2>
31. Dominguez A, & Geyer R (2017) Photovoltaic waste assessment in Mexico. *Resources, Conservation & Recycling*, 127:29–41. <https://doi.org/10.1016/j.resconrec.2017.08.013>
32. IRENA and IEA PVPS. (2016). End-of-life management. Solar photovoltaic panels. International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems Programme. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf
33. Sariatli F (2017) Linear Economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. *Visegrad Journal of Bioeconomy and Sustainable Development* 6:31–34. <https://doi.org/10.1515/vjbsd-2017-0005>
34. Gautam A, Shankar R, Vrat P (2021) End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy. *Sustain Prod Consum* 26:65–77. <https://doi.org/10.1016/j.spc.2020.09.011>
35. Nawaz I, Tiwari GN (2006) Embodied energy analysis of photovoltaic (PV) system based on macro- and micro level. *Energy Policy* 34:3144–3152. <https://doi.org/10.1016/j.enpol.2005.06.018>
36. Muthu M, Victor K, Rajasekaran R (2014) Energy pay back period and carbon pay back period for solar photovoltaic power plant. *Int J Chem Sci* 12:293–305
38. EU-India TCP. (2021) PV waste management in India. Comparative Analysis of State of Play & Recommendations. EU-India: Technical Cooperation - Energy Project. Retrieved from <https://www.solarpowereurope.org/wp-content/uploads/2021/02/PV-Waste-Management-Report-25-01-2021.pdf>
39. Kapoor K, Pandey KK, Jain AK, Nandan A (2014) Evolution of solar energy in India: a review. *Renew Sust Energ Rev* 40:475–487. <https://doi.org/10.1016/j.rser.2014.07.118>
40. MERCOM. (2016) Q4 2016 India solar market update – 2016 solar installations to reach 4 GW. Retrieved from MERCOM India: <https://mercomindia.com/product/q4-2016-india-solar-update/>
41. MERCOM. (2018) India solar market - December 2018. Mercom India Research . Retrieved from <https://mercomindia.com/wp-content/uploads/2018/12/Mercom-Intersolar-India-Solar-Market-Update-Whitepaper.pdf>
42. MERCOM. (2019). India solar market - May 2019. Mercom India Research. Retrieved from https://mercomindia.com/wp-content/uploads/2019/06/Mercom-SNEC_India-Solar-Market-Update-Whitepaper.pdf
43. MERCOM. (2020) Q2 2020 India solar market update – 205 MW INSTALLED IN Q2 2020. Retrieved from MERCOM India: <https://mercomindia.com/product/q2-2020-india-solar-market-update/>
44. MERCOM. (2020) India on pace to install 65 GW of solar by 2022, far off the 100 GW goal. Retrieved from MERCOM India: <https://mercomindia.com/india-pace-install-solar-2022/#:~:text=In%202015%2C%20the%20NDA%20administration,from%20the%20rooftop%20solar%20sector.>
45. MERCOM India. (2020) Q1 2020 India solar market update – 1,080 MW installed in Q1 2020. Retrieved from MERCOM India: <https://mercomindia.com/product/q1-2020-india-solar-market-update/>
46. Cambridge Econometrics. (2020) E3-India manual 2020. Cambridge: Cambridge Econometrics. Retrieved from <https://www.camecon.com/how/e3-india-model/>
47. Home Scape. (2019) DIY calculation guide for 1 kW solar system. Retrieved from Home Scape by Amplus Solar: <https://homescape.solar/diy-calculation-guide-for-1kw-solar-system/#:~:text=As%20a%20thumb%20rule%2C%20you,1%20kW%20solar%20system%20capacity.>
48. World Bank. (2018) Global Solar Atlas. World Bank Group. Retrieved from <https://globalsolaratlas.info/download/india>
49. Yue D, You F, Darling SB (2014) Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: life cycle energy and environmental comparative analysis. *Sol Energy* 105:669–678. <https://doi.org/10.1016/j.solener.2014.04.008>
50. Rajput P, Tiwari GN, Sastry OS, Bora B, Sharma V (2016) Degradation of mono-crystalline photovoltaic modules after 22 years of. *Sol Energy*:786–795. <https://doi.org/10.1016/j.solener.2016.06.047>
51. Patel K (2018) Solar panel efficiency and lifespan. Retrieved from Solar Energy for Us: <https://solarenergyforus.com/solar-panel-efficiency-lifespan/#:~:text=highest%20efficiency%20for%20polycrystalline%20cell,lifespan%20ranges%20around%2025%20years.>
52. Wong JH, Royapoor M, Chan CW (2016) Review of life cycle analyses and embodied energy requirements of single crystalline and multi-crystalline silicon photovoltaic systems. *Renew Sust Energ Rev* 58:608–618. <https://doi.org/10.1016/j.rser.2015.12.241>

53. Latunussa CE, Mancini L, Blengini GA, Ardente F, & Pennington D (2016) Analysis of material recovery from silicon photovoltaic panels. Publications Office of the European Union. Retrieved from <https://publications.jrc.ec.europa.eu/repository/handle/JRC100783>
54. Markert E, Celik I, Apul D (2020) Private and externality costs and benefit of recycling crystalline silicon (c-Si) photovoltaic panels. *Energies* 13. <https://doi.org/10.3390/en13143650>
55. EU. (2012) Directive 2012/19/EU of the European Parliament and the COuncil of 4 July 2012 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union. Retrieved from <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:en:PDF>
56. Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M, & Wind-Scholten M (2011) Methodology guidelines on life- cycle assessment of photovoltaic electricity, 2nd Edition, IEA PVPS Task 12. International Energy Agency Photovoltaic Power systems Programme. Retrieved from https://iea-pvps.org/wp-content/uploads/2020/01/rep12_11.pdf
57. Svarc J (2020) Most efficient solar panels 2020. Retrieved from Clean Energy Reviews: <https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels>
58. Gupta A (2018) 21 - Energy return on energy invested (EROI) and energy payback time (EPBT) for PVs. In T. M. Letcher, & V. M. Fthenakis, A Comprehensive Guide to Solar Energy Systems. With Special Focus on Photovoltaic Systems (pp. 407-425). Academic Press. <https://doi.org/10.1016/B978-0-12-811479-7.00021-X>
59. Government of India. (2019). Standing committee on energy (2018-2019). New Delhi: Lok Sabha Secretariat, Government of India. Retrieved from http://164.100.47.193/lssccommittee/Energy/16_Energy_43.pdf
62. Somvanshi A (2013) Embodied energy demystified. Retrieved from DownToEarth: <https://www.downtoearth.org.in/coverage/embodied-energy-demystified-40064>
60. MNRE (2019) Annual Report 2018-19. Ministry of New and Renewable Energy, Government of India, New Delhi Retrieved from https://mnre.gov.in/img/documents/uploads/file_f-1608040317211.pdf
61. IRENA. (2019) Renewable power generation costs in 2019. Abu Dhabi: International Renewable Energy Agency. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf
37. Sica D, Malandrino O, Supino S, Testa M, & Lucchetti MC (2018) Management of end-of-life photovoltaic panels as a step towards a circular economy. *Renew Sust Energ Rev* 2934-2945. <https://doi.org/10.1016/j.rser.2017.10.039>

Affiliations

Vishnu S Prabhu¹ • Shraddha Shrivastava¹ • Kakali Mukhopadhyay^{1,2}

¹ Gokhale Institute of Politics and Economics, Pune, India

² Department of Agricultural Economics, McGill University, Macdonald Campus, 21,111 Lakeshore Road, Ste Anne de Bellevue, Montreal, Quebec H9X3V9, Canada