CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Addressing the Impending Crisis of Solar Photovoltaic Waste in India

A Comprehensive Recycling Framework With Policy Solutions

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Center for Study of Science, Technology and Policy

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Designed and Edited by CSTEP

Disclaimer

Contributors: Anjali Taneja, Khushboo Garg, Revathy S M, and Thirumalai N C.

(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)

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Center for Study of Science, Technology and Policy

Bengaluru

18, 10th Cross, Mayura Street
Papanna Layout, Nagashettyhalli
RMV II Stage, Bengaluru 560094
Karnataka (India)

Noida

1st Floor, Tower-A
Smartworks Corporate Park
Sector 125, Noida 201303
Uttar Pradesh (India)

Tel.: +91 (80) 6690 2500
Email: cpe@cstep.in

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Executive Summary

The solar photovoltaic industry is witnessing a remarkable expansion worldwide. India is ranked fourth globally in ground-mounted photovoltaic deployment. While this is impressive, the waste resulting from such end-of-life photovoltaic panels is expected to be enormous at 4.5 million tonnes by 2050, as per our estimates. In the absence of suitable infrastructure facilities and a lack of proactive policies for recycling, waste accumulation can become an unmanageable problem.

To address this, we propose a recycling framework that prioritises the establishment of clusters, collection centres, and recycling units to minimise transport costs and distances. To deduce the framework's efficacy, it was applied to Karnataka, India. We also evaluated the country's global standing in terms of policy and recycling maturity levels and identified policy imperatives for the effective execution of the recycling framework for a seamless transition to the circular economy. Further, we investigated opportunities in business expansion and investment promotion to facilitate effective waste management.

This study highlights the importance of establishing a comprehensive monitoring and reporting system in India and regular engagements among policymakers, industry, civil society, and academia to foster sustainable circular economy practices in photovoltaic waste management.

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Abbreviations

AHC	Agglomerative Hierarchical Clustering
CC	Collection Centre
CdTe	Cadmium Telluride
C	Cluster
CSTEP	Center for Study of Science, Technology and Policy
c-Si	Crystalline Silicone
EOL	End-of-Life
EPR	Extended Producer Responsibility
GIS	Geographic Information System
GW	Gigawatt
IRENA	International Renewable Energy Agency
KIADB	Karnataka Industrial Area Development Board
KREDL	Karnataka Renewable Energy Development Limited
M&R	Monitoring and Reporting
MOEFCC	Ministry of Environment, Forest and Climate Change
MNRE	Ministry of New and Renewable Energy
MW	Megawatt
NREL	National Renewable Energy Laboratory
PIB	Press Information Bureau
PRO	Producer Responsibility Organisation
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
RU	Recycling Unit
TPA/tpa	Tonnes per Annum
TPD/tpd	Tonnes per Day

1. Introduction

As the world progresses toward a sustainable green energy future, it is witnessing a remarkable expansion in the solar industry. This has escalated the volume of end-of-life (EOL) panels, posing significant environmental challenges. According to the International Renewable Energy Agency, global solar photovoltaic (PV) waste will reach a staggering 78 million tonnes by 2050 (IRENA, 2016). While this is worrisome, it presents an opportunity for material recovery and the economy (Farrell, C. C., 2020; Kim, H. & Park, H., 2018; Rabaia, M. K. H., 2022).

With an impressive installed PV capacity of 64 GW (PIB, 2023), India is projected to generate approximately 4.5 million tonnes of PV waste by 2050. Therefore, it is crucial to acknowledge the importance of PV waste management in India.

In 2022, the handling of PV waste in India was brought under the e-waste guidelines by the Ministry of Environment, Forest and Climate Change (MoEFCC); however, the policies and regulatory framework governing PV waste handling remain ambiguous. Moreover, India does not have a robust recycling framework to enable the recycling and repurposing of solar PV waste.

To address this issue, this study has put together a scientific recycling framework to manage the burgeoning solar PV waste in India. Moreover, this study examined the progress of solar PV waste management in India vis-à-vis other countries and the potential to reuse and repurpose this waste. The following research questions are addressed in this study:

1. What is the expected quantum of solar PV waste in India, and how is the country globally positioned at policy and recycling maturity levels?
2. How can India resolve the solar PV waste problem?
3. What are the policy imperatives required in India for a smooth transition to the circular economy in solar PV waste management?
4. What is the scope for business expansion and investment promotion to enable effective solar PV waste management in India?

This study also underlines a set of recommendations for policymakers to allow effective implementation of the recycling framework in India. Various suggestions are also provided for industry and off-takers to capitalise on emerging business opportunities in solar PV waste management.

2. Materials and methods

2.1 Composition, disposal mechanism, and potential for recovery

In India, the majority of PV modules (approximately 93%) is made of crystalline silicone (c-Si), with cadmium telluride (CdTe) thin film modules accounting for approximately 7% of PV modules (Taneja, A. & Garg, K., 2023).

A typical c-Si module consists of several components, including a glass sheet, an aluminium frame, an encapsulant, a back sheet, copper wires, and silicon wafers (Aberle, A. G., 2009). Silver, tin, and lead are also used for manufacturing c-Si modules. On the other hand, a CdTe thin-film module primarily comprises glass, encapsulant, and compound semiconductors (Barbato, M., 2021; Ferekides, C. S., 2004).

As these PV panels approach their EOL, the frames from the modules are extracted and sold as scrap junk, whereas the junctions and cables are recycled according to India's e-waste rules. The glass laminate undergoes partial recycling, while the remaining portion is disposed of as general waste. Moreover, silicon and silver can be extracted by incinerating the module in furnaces. Generally, only approximately 20% of PV waste is effectively recovered, with the remaining waste often being informally treated (Taneja, A. & Garg, K., 2023).

If effectively reinstated into the economy, the recovered materials from PV waste may exceed a value of USD 15 billion by 2050 globally (IRENA, 2016). These materials could be used for producing approximately 2 billion new panels or be introduced into global commodity markets (Weckend, S., 2016). This not only enhances the security of future PV supply but also contributes to the availability of raw materials for other industries reliant on such resources (Bogacka, M., 2020; Gautam, A., 2021). Therefore, more efficient methods must be developed for effective PV waste management.

2.2 India's PV waste projections, global comparisons, and existing challenges

As of March 2023, India has nearly 64 GW (PIB, 2023) of solar PV installations, which are projected to generate solar PV waste of approximately over 4 million tonnes by 2050. Figure 1 depicts the state-wise PV waste by 2050, estimated on the basis of current solar PV installations.

Rajasthan, Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, and Telangana are expected to be the top six Indian states for PV waste generation, accounting for nearly 77% of the total PV waste.

a

b

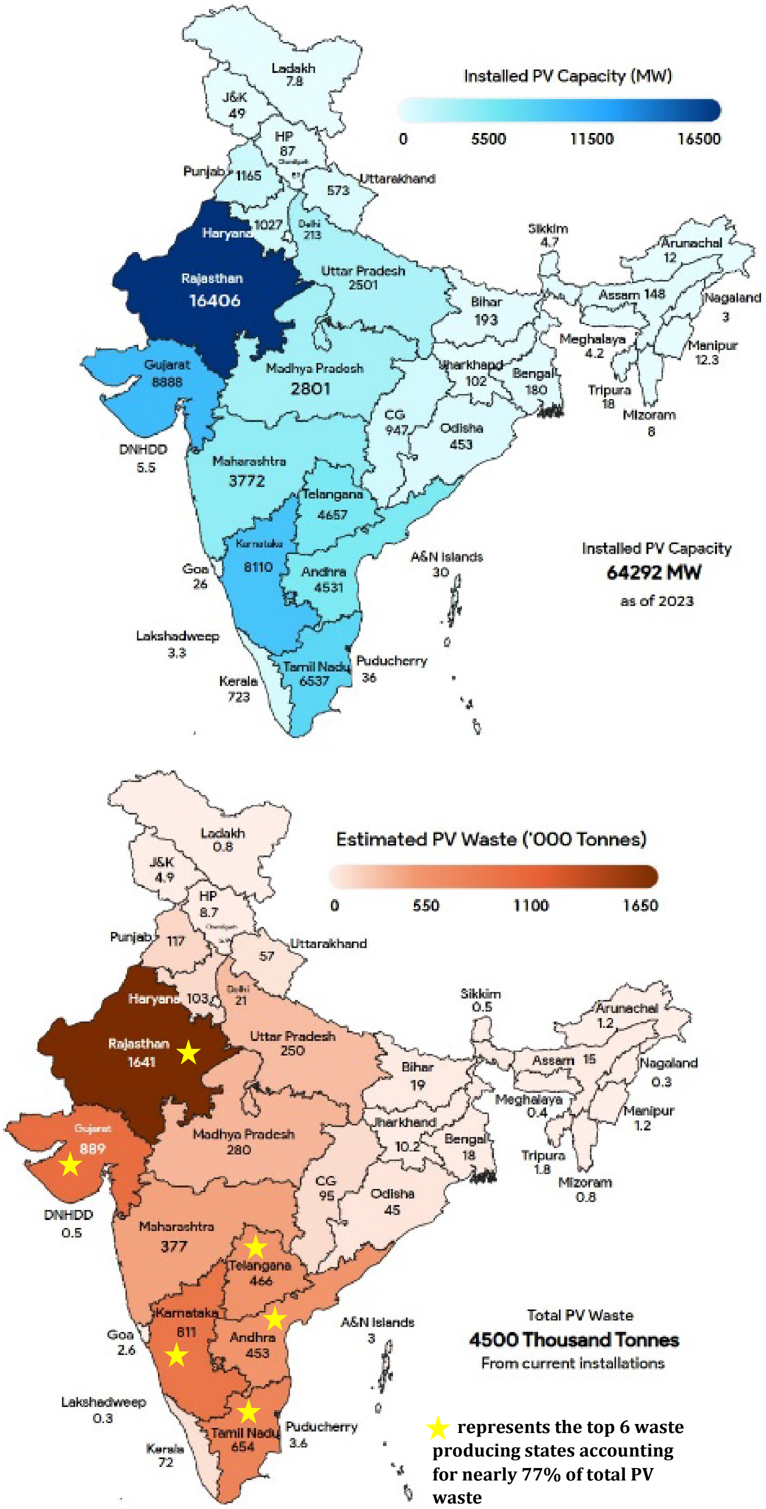


Figure 1: (a) Current installed PV capacity (MNRE, 2022); (b) Estimated PV waste generation by 2050

Although India has initiated efforts to establish policies and regulations for PV waste management, there remains ambiguity concerning the maturity levels in policy and recycling measures.

This study examined levels of policy and recycling maturities for the global economies vis-à-vis India. On the basis of the measuring criteria (Table 1), this study positioned global economies and India under low, medium, and high categories. The findings are depicted in Figure 2.

Table 1: Parameters considered by the study to measure the levels of policy and recycling maturity

Parameters	Measuring criteria
Policy maturity	1. Clearly defined policy directives or regulations on solar PV waste management. 2. Availability of central insurance agency or producer responsibility organisations. 3. Schemes and investments for PV waste recycling, research and development (R&D), etc.
Recycling maturity	1. Well-defined guidelines and recycling benchmarks or targets. 2. Active engagements with the government and other regulatory bodies for setting up fees, targets, etc. 3. Active R&D initiatives, programmes in technology development, and innovative recycling practices.

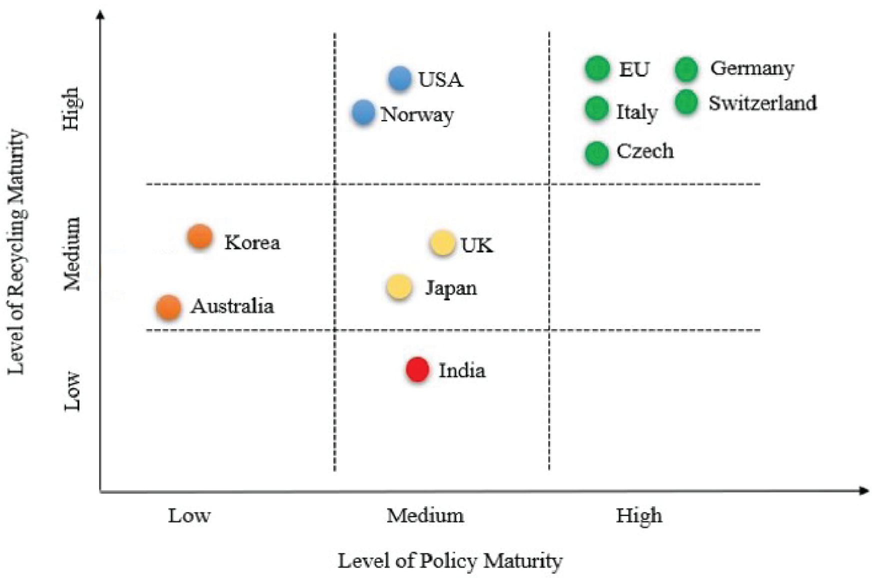


Figure 2: Policy maturity versus recycling maturity levels for India vis-a-vis other countries

The results indicated that global economies fare better than India. For example, in the United States, PV waste is considered as a part of solid or hazardous waste, with each state having the autonomy to establish its own recycling rules. Japan, on the other hand, is actively investing in developing and testing recycling technologies although no mandatory recycling guideline exists. Korea lacks specific guidelines on PV waste management but has a series of funded initiatives for developing recycling technologies, besides the formation of a PV recycling centre.

In comparison, India has medium and low policy and recycling maturity, respectively. This is because of some of the inherent challenges and issues (Table 2) prevailing in the country on the technology and policy fronts of solar PV waste management.

Table 2: Policy and technology barriers for solar PV waste management in India

Policy barriers	Technology barriers
Excessive involvement of the informal sector in solar PV waste handling. At present, a majority of PV waste is either stored or disposed of in landfills.	Lack of suitable technologies or tools to track PV waste generation.
No clear segregation between e-waste and PV waste handling guidelines and regulations. Moreover, there exists no penalty or landfill tax.	Existence of outdated recycling technologies and ineffective recycling processes. Dependency on a single type of PV module could not only deplete natural resources but also inhibit recycling and recovery capacities.
Absence of a national monitoring and reporting agency to examine, evaluate, report, and regulate the quantum of waste produced, recycled, or reused.	Lack of availability of profitable business opportunities or inadequate knowledge of the potential options for business expansion in the solar PV waste management sector for the industry and off-takers.
Lack of suitable infrastructure for collection, cost-effective transportation, and recycling of PV waste.	Absence of adequate R&D programmes, efforts, and initiatives to promote domestic manufacturing of PV panels and proper recycling and repurposing of PV waste.
Lack of adequate information dissemination through proper channels [for example, information on recycling rates, Extended Producer Responsibility (EPR) guidelines, technology developments, new policies, laws and regulations, job avenues, or employment opportunities] due to a limited number of engagements and collaborative exchanges between the government, industry, civil society, and academia.	
Absence of defined recycling targets or standardised recycling benchmark specifications.	

Moreover, the presence of toxic materials, such as cadmium in thin films and lead in the crystalline cells of a PV panel, can negatively impact the environment, humans, and animals. The development of a cutting-edge PV waste recycling system, therefore, becomes imperative to address these challenges effectively.

2.3 Recycling framework

This study has put together a comprehensive recycling framework to enable effective and timely recycling of PV waste.

2.3.1 Components

The recycling framework consists of the following three main components:

a. 'Clusters' (addressed as Cs) are groups of PV plants that share common characteristics or are located near each other.

   The analysis of Cs serves as a valuable data exploration and mining tool, facilitating the division of a multivariate dataset into distinct and meaningful Cs or groups. In this study, groups or Cs of PV plants were identified on the basis of their proximity in terms of distance and the quantity of waste generated by each plant.

b. 'Collection Centres' (addressed as CCs) are designated PV plants within each C that serve as collection points for EOL or failed panels from other PV plants within the C. These CCs store the panels temporarily before being transported for recycling. In this study, the CCs within each C were strategically located by considering the proximity to the PV plants and the overall transportation costs.

c. 'Recycling Units' (addressed as RUs) are facilities established in an optimal industrial zone to recycle PV waste.

An RU should be established either at the shortest road distance from the designated CC or the cost of transporting PV waste, via road, from the CC to the potential RU should be minimum.

The following scientific methodologies were followed to determine the Cs, CCs, and potential locations of RUs:

A. The Geographic Information System (GIS) was deployed to determine the latitude and longitude of the PV plants and industrial zones. It was also used for determining the road distance between the PV plants and that between the PV plants and industrial zones.

B. Optimisation modelling was undertaken to determine the optimal CCs to store the PV waste and the optimal locations where the RUs could be set up for PV waste recycling.

Mathematical optimisation involves defining an objective function, which represents the desired output to be maximised or minimised. The variables within the optimisation problem are the controllable inputs, and the constraints are equations that restrict the magnitude of these variables.

Optimisation techniques provide significant advantages over traditional trial-and-error methods as they offer systematic and efficient approaches to problem-solving. By utilising mathematical optimisation, this study could effectively evaluate a range of scenarios and identify the optimal choices for CCs and RUs.

To gain real-time insights and inputs, we consulted subject matter experts from Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH, the National Solar Energy Federation of India, the National Institute for Transforming India Aayog, The Energy and Resources Institute, Solar Energy Corporation of India Ltd., and First Solar.

2.3.2 Data source and assumptions

To create a comprehensive recycling framework for solar PV waste management, this study collected data from ground-mounted commissioned PV plants and government-approved industrial zones.

Table 3: Assumptions made for optimisation modelling

Solar PV panel/ PV module	Transport	Solar PV waste	RU
As the most common technology in India, c-Si is considered the technology for a solar PV module or panel.	Transportation of EOL panels from PV plants to CCs and from CCs to RUs is carried out via the road by using container trucks.	A regular loss scenario i.e., a 25-year lifetime for solar PV modules with no early attrition is considered.	Expected to be operational throughout the year (365 days).
This study considered PV modules of 250 W, 72 cells, and 2 m² (based on consultations with experts).	The multi-axel container truck has a capacity of 16 tonnes, with a dimension (ft) of 32 L × 8 W × 8 H (based on consultations with experts).	The annual failure rate of the PV panels in a plant is considered as 0.05% (NREL, 2017).	The transport of PV waste from the CCs is performed annually.
A typical 250-W solar panel weighs 25 kg (based on consultations with experts).	A total of 732 panels can be safely stacked in the container truck of the above-mentioned dimension (based on the authors' calculation).	In the regular loss scenario, the EOL of panels is considered (IRENA, 2016).	
The dimension (ft) of the module is 5.5 L × 3.25 W × 0.13 H (based on consultations with experts).	The cost of transport is INR 3.6/metric tonne km (NITI Aayog, 2021 and consultations with experts).		
The number of panels required for a capacity of 1-MW PV plant (with a capacity of 250 W) is 4000.			

2.4 Stage-wise framework

The stage-wise optimisation-modelling-driven recycling framework is depicted in Figure 3.

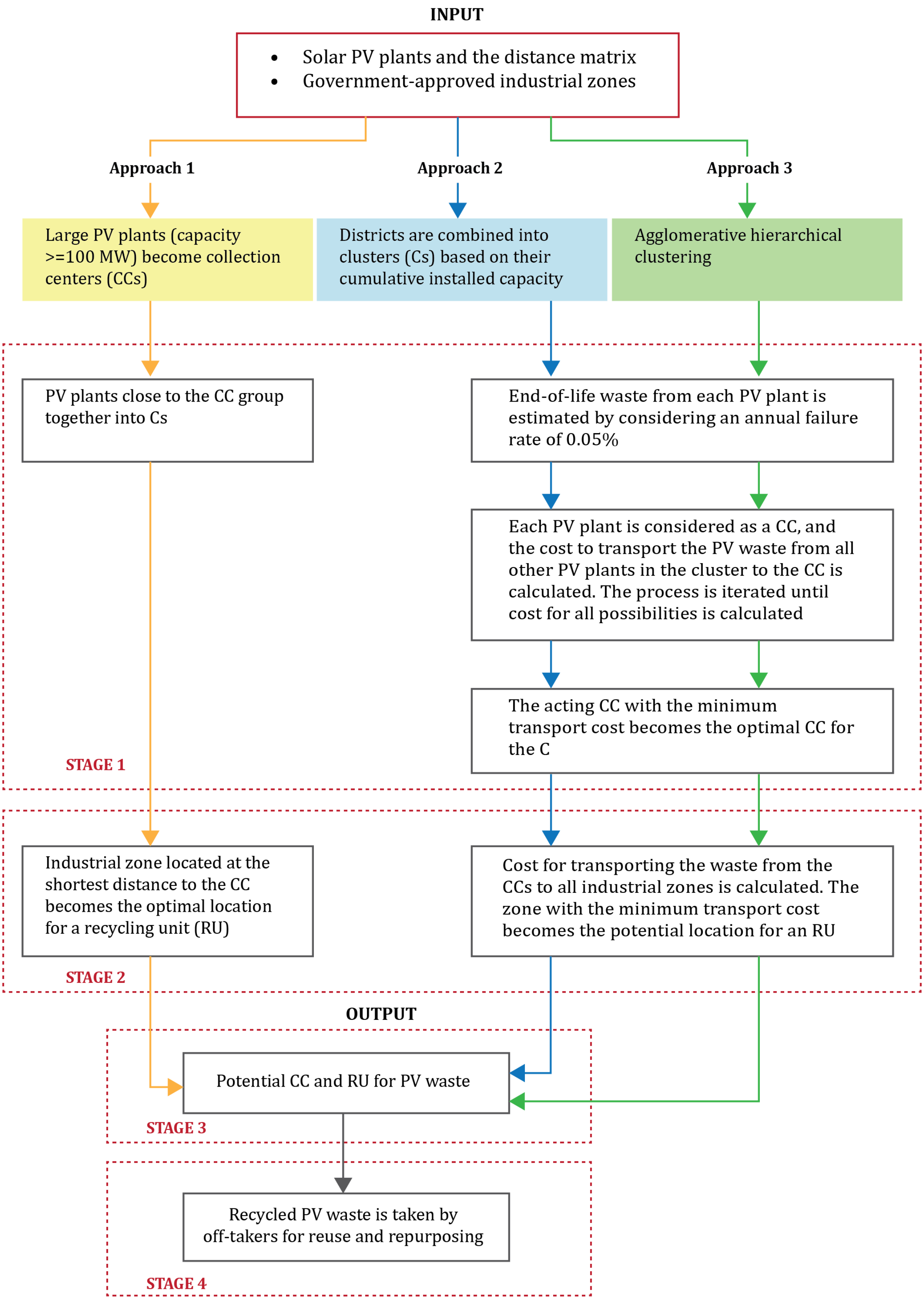


Figure 3: Solar PV waste recycling framework

Broadly, the framework encompasses the following four stages in all three approaches:

Stage 1
An input is a dataset of PV plants and industrial zones

Stage 2
Identification of Cs and CCs by using optimisation modelling

Stage 3
Identification of optimal locations for setting up RUs by using optimisation modelling

Stage 4
Closing the loop wherein the off-takers and industry reuse or repurpose the recycled waste

3. Calculation

The following are the mathematical explanations of the three approaches:

A. Approach 1

The 'shortest distance' is considered for identifying the optimal location for an RU. A PV plant of preferably higher capacity is considered as the CC, and the plants in the vicinity of the CC are grouped to form a C. The industrial zone nearest to the CC is identified as the potential location for the RU.

This approach assumes that waste generation from PV plants is directly correlated with their installed capacities. Therefore, plants with higher capacities will produce a greater amount of waste, both at the time of their annual degradation and EOL.

B. Approach 2

The 'minimum transport cost' and 'shortest distance' are used for identifying the CC and locating the optimal location for an RU. Before identifying CCs, Cs are identified on the basis of district-wise cumulative installed capacity. The identification of a CC within each C is performed using a cost-minimisation method. Finally, the industrial zone nearest to the CC is identified as the potential location for the RU.

Cost minimisation is performed using the following formula:

Cost array C_{ij} can be denoted as,

$$C_{ij} = \sum_{k}^{m} d_{kj}\, w_k f \;\forall\; k \in j$$

or

$$\begin{bmatrix} C_{i1} \\ \vdots \\ C_{im} \end{bmatrix} = \begin{bmatrix} d_{11} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mm} \end{bmatrix} \begin{bmatrix} w_{i1} \\ \vdots \\ w_{im} \end{bmatrix} \times f$$

Where,

i = number of Cs

j = m_i plants under each C

d_{kj} = distance between plant k and j (km)

w_k = waste generated at the k^{th} plant (tonnes/annum)

f = transport cost (INR per metric tonne – kilometre)

Therefore, the CC for the i^{th} C, i.e., CC_i is identified using the following equation:

$$CC_i = \left[j \forall\, C_{ij} = \min\{C_{ij}\} \right]$$

C. Approach 3

The 'minimum transport cost' is considered for locating the optimal location for an RU. Agglomerative hierarchical clustering (AHC) is deployed to determine the number of Cs. The identification of the CC within each C is performed by using the cost-minimisation method, which is also used to identify the potential RU location.

The clustering algorithm of AHC clusters the data on the basis of the similarity between data points. Each data point (PV plant) is initially considered as an individual C, and all existing Cs are gradually merged at each step, following a bottom-up approach. This hierarchical clustering process is performed through computer modelling.

In this study, the centroid linkage method of AHC was used, considering the cumulative waste generated by PV plants. The approach assigns weights to each data point on the basis of the distance between the data points and waste generation, thereby determining the Cs.

Mathematically, the association between two Cs, for instance, C1 and C2 can be reflected as $\mathrm{D}_{12} = (\bar{\mathrm{x}}, \bar{\mathrm{y}})$, where x_i is the elements from C1 and y_i is the elements from C2. The clustering is represented by a dendrogram, which can be traversed to obtain the desired clustering structure.

4. Results

To show the feasibility of the recycling framework, this study examined and assessed its applicability in Karnataka, India. The results of the optimisation modelling are presented below.

4.1 Installed PV capacities and waste projections in Karnataka

Karnataka is currently ranked third nationwide in installed PV capacities, with a total installed capacity of 8110 MW (MNRE, 2022). A favourable climate characterised by abundant solar irradiation has significantly contributed to the expansion of the solar industry in Karnataka. The recently introduced Karnataka Renewable Energy Policy 2022-2027 by the Karnataka Government aims to further deepen the RE market in the state and attract investments in the sector. However, a gap in addressing the problem of PV waste management persists.

According to the results, Karnataka is projected to have nearly 24 GW of solar PV capacity by 2030 and nearly 69 GW by 2050.

Karnataka has set an ambitious target of adding 10 GW of RE by 2027 (KREDL, 2022). Considering the current installed capacity of the state and assuming that nearly 90% of the target capacity of 10 GW will be contributed by solar PV, this study performed linear projections (Figure 4).

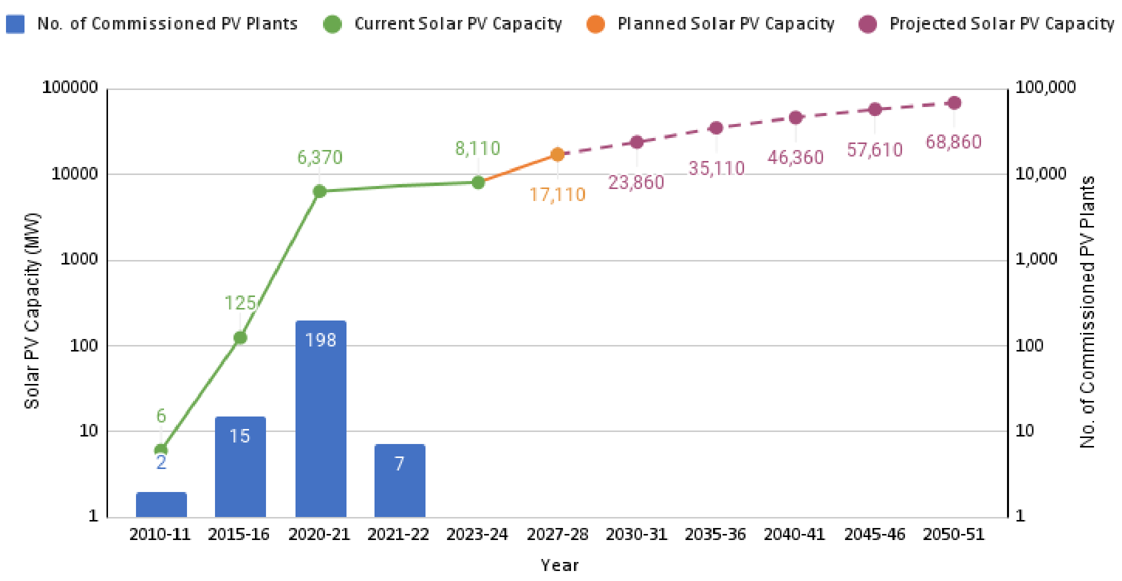


Figure 4: Installed PV capacity projections for Karnataka

The projections also indicate that Karnataka will generate 0.5 million tonnes of PV waste by 2050. Figure 5 depicts the district-wise expected waste generation in the state.

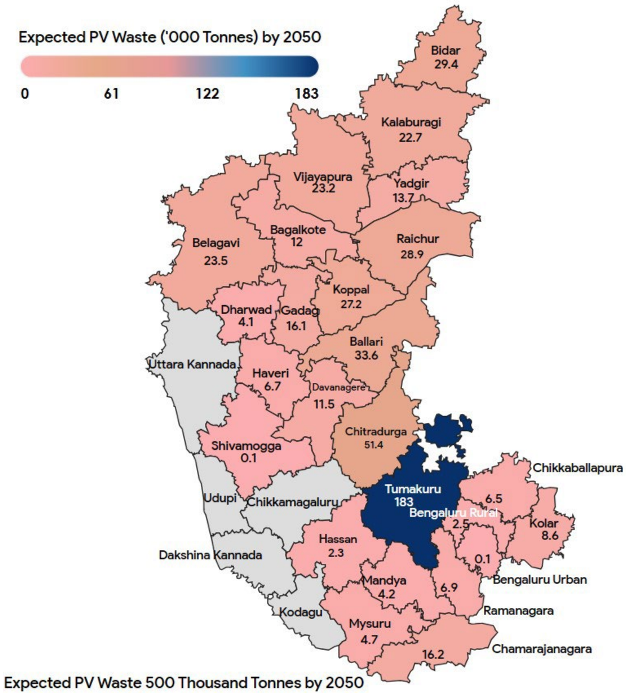


Figure 5: Solar PV waste projections for Karnataka

Therefore, sound strategies and robust policies are required for managing the massive EOL PV waste, which may accumulate in the future.

4.2 Deployment of the recycling framework

4.2.1 Dataset

This study considered the latest database of 313 ground-mounted PV plants from Karnataka Renewable Energy Development Limited (KREDL, 2022), with the plants being under different ownerships, i.e. single or partnership industries. Further, the latest database of 31 government-sanctioned industrial areas developed by the Karnataka Industrial Area Development Board was considered (KIADB, 2022).

4.2.2 GIS tool

The PV plant database was structured using a GIS tool. Of the 313 PV plants, a few are under construction, affected by procedural delays, or yet to be initiated. Therefore, this study narrowed down to 222 operational PV plants, with their latitude and longitude coordinates. Figure 6 depicts the spread of these PV plants (with a capacity of 6737 MW) and 31 industrial areas.

The tool was also deployed to calculate the road distances between the PV plants and those between the PV plants and industrial zones to derive distance matrices of 222 × 222 and 222 × 31, respectively.

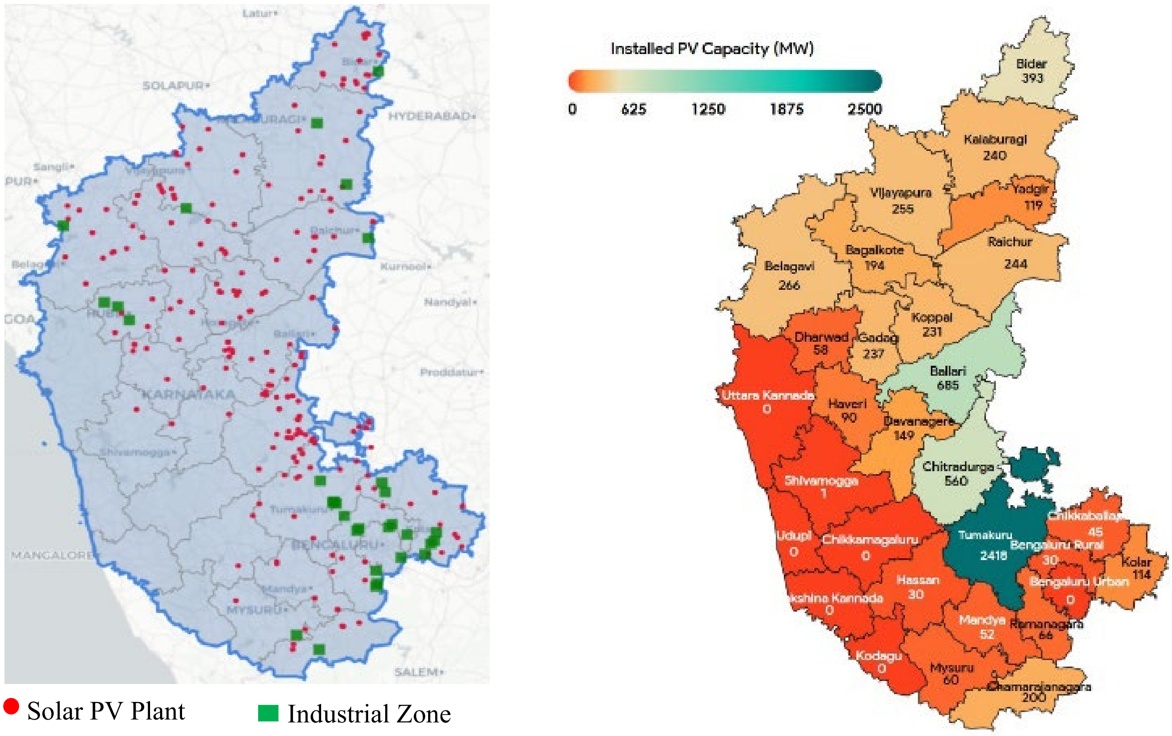


Figure 6: (a) Geospatial spread of PV plants and industrial zones in Karnataka (b) Installed PV capacity of 222 plants (KREDL, 2022)

4.2.3 Waste projection

The commissioning of solar PV plants in Karnataka began in 2009, and approximately 95% of the 222 PV plants were commissioned before 2020.

This study calculated the waste generation (W) by the EOL using the following formula:

$$W = I_c N_p F_a W_p$$

Where,

I_c = Installed capacity (MW)

N_p = Number of panels per MW

F_a = Standard annual failure rate of 0.05%

W_p = Weight of one panel (tonnes)

Figure 7 depicts the current and expected PV waste generation in Karnataka. Considering the commissioning dates of the 222 PV plants, over 90% of these plants are expected to decommission between 2040 and 2050.

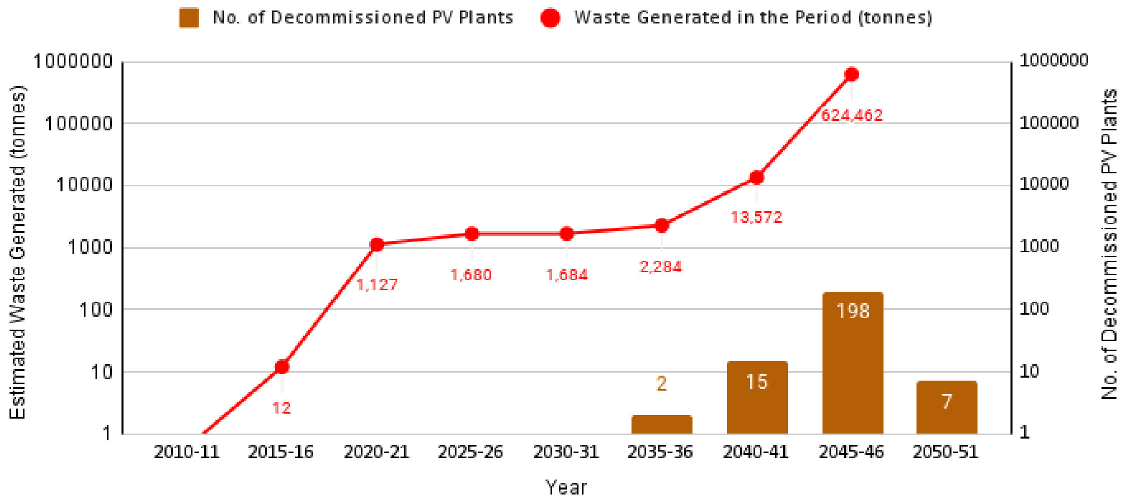


Figure 7: PV waste generation (current and projected) in Karnataka

As per the current e-waste regulations (PIB, 2022), the failed panels can be stored for the next decade. However, a substantial volume of PV waste will be generated thereafter.

4.2.4 Findings of optimisation modelling

4.2.4.1 Approach 1: Installed-capacity-based clustering of PV plants

To determine the CCs, this study examined the PV plants with higher installed capacity from the dataset of 222 plants.

According to Figure 8, approximately 75% of the plants have capacities below 30 MW, and 3% of the plants have capacities > 100 MW, including Pavagada Solar Park (with 2050 MW).

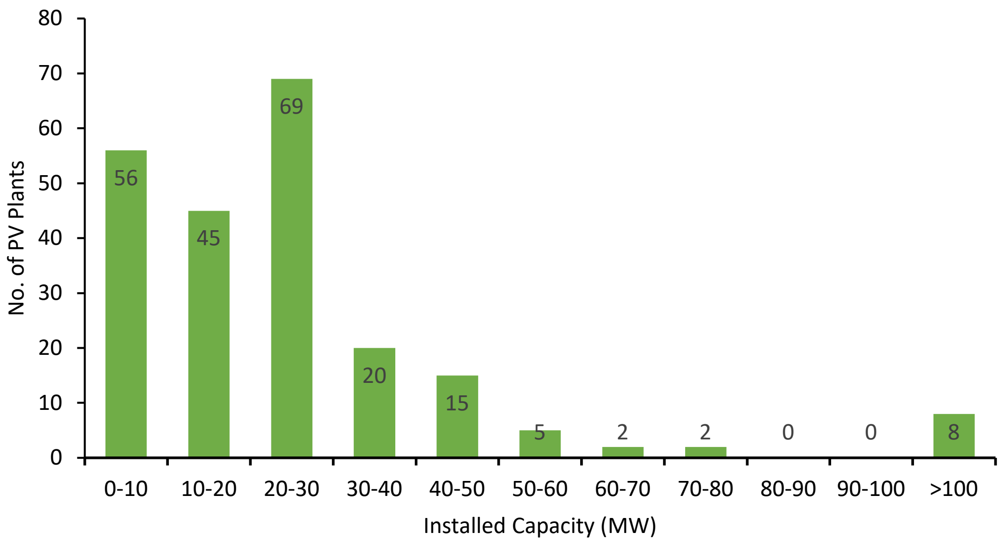
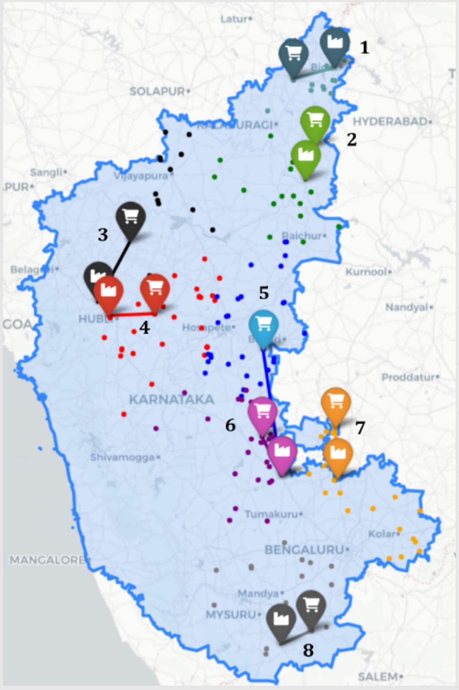


Figure 8: Distribution of PV plants based on installed capacity

The 8 PV plants were designated as CCs, and those located in closest proximity to these CCs were grouped into 8 Cs. Thereafter, the industrial areas situated at the shortest distance from the CCs were identified as optimal locations for RUs.

> ***Approach 1 in this study identified '8 Cs, 8 CCs, and 7 RUs' (Figure 9).***

Notably, 3 RUs were identified in the central region of Karnataka, indicating the presence of higher capacity plants commissioned in this area. This distribution suggests that the clustering and RU allocation are aligned with the concentration of PV plants and their waste generation.

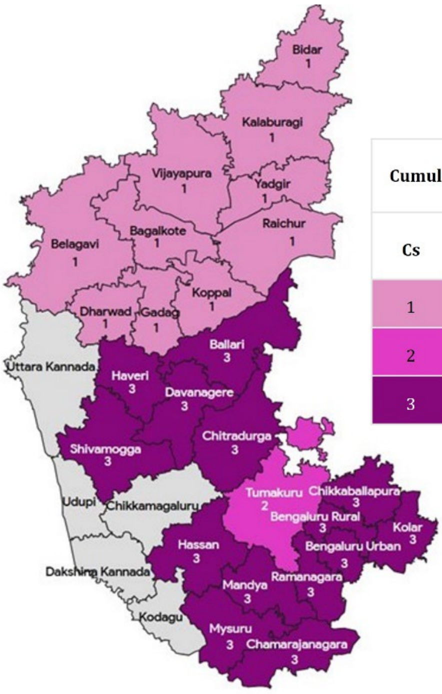


Identified districts for CCs, optimal locations for RUs, and estimated EOL PV waste			
S.No.	**CC districts**	**Potential RU zones**	**Total EOL PV waste collected in Cs (in tonnes)**
1	Bidar	Bidar	41
2	Kalaburagi	Yadgir	49
3	Belagavi	Dharwad	66
4	Gadag	Dharwad	64
5	Bellary	Tumakuru	89
6	Chitradurga		85
7	Tumakuru	Chikkaballapur	238
8	Chamrajnagar	Chamrajnagar	42

Figure 9: Findings of Approach 1

4.2.4.2 Approach 2: Clustering of PV plants on the basis of district-wise cumulative installed capacity

This study calculated the district-wise cumulative installed capacities of 222 PV plants by using their spread and waste generation and grouped the districts into three Cs—northern, central, and southern. The C-wise cumulative installed capacities are presented in Figure 10.

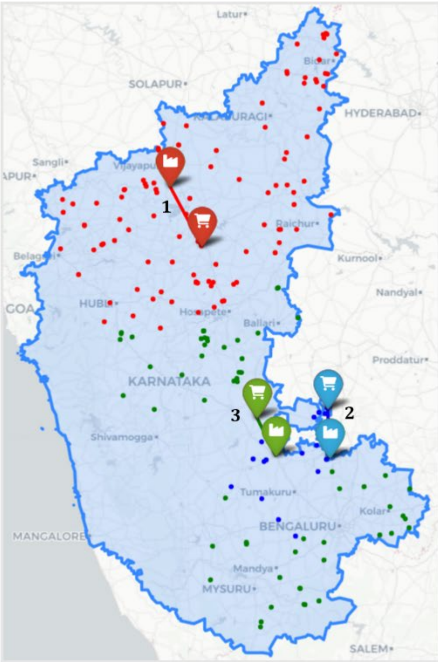


Cumulative installed PV capacity of identified Cs	
Cs	**Cumulative installed PV capacity (MW)**
1	2237
2	2418
3	2082

Figure 10: Clusters based on the district-wise cumulative installed PV capacities

After predefining the Cs, the PV plant with the minimum cost of transporting PV waste through the road from all other plants in the C was identified as the CC through the cost-minimisation method. Thereafter, the industrial areas situated at the shortest distance from CCs were identified as optimal locations for RUs.

Approach 2 identified '3 Cs, 3 CCs, and 3 RUs' (Figure 11).



Identified districts for CCs, optimal locations for RUs, and estimated EOL PV waste

S.No.	CC districts	Potential RU zones	Total EOL PV waste collected in Cs (in tonnes)
1	Bagalkote	Vijaypur	112
2	Tumakuru	Chikkaballapur	121
3	Chitradurga	Tumakuru	104

Collection Centre (CC)
Recycling Unit (RU)
Solar PV Plant

Figure 11: Findings of Approach 2

4.2.4.3 Approach 3: AHC-based clustering of PV plants

This study adopted AHC to identify the ideal number of Cs. The clustering process began with the distance matrix of 222 × 222 PV plants, where each plant was treated as an individual C. By considering proximity and waste generation, the clustering algorithm progressively groups the plants, resulting in a hierarchical structure. Considering the PV panel dispersion and estimated waste generation, 6 Cs were identified. Subsequently, CCs and the optimum locations for RUs were determined using the cost-minimisation method. The step-wise Approach 3 with the final output for Karnataka is explained in Figure 12.

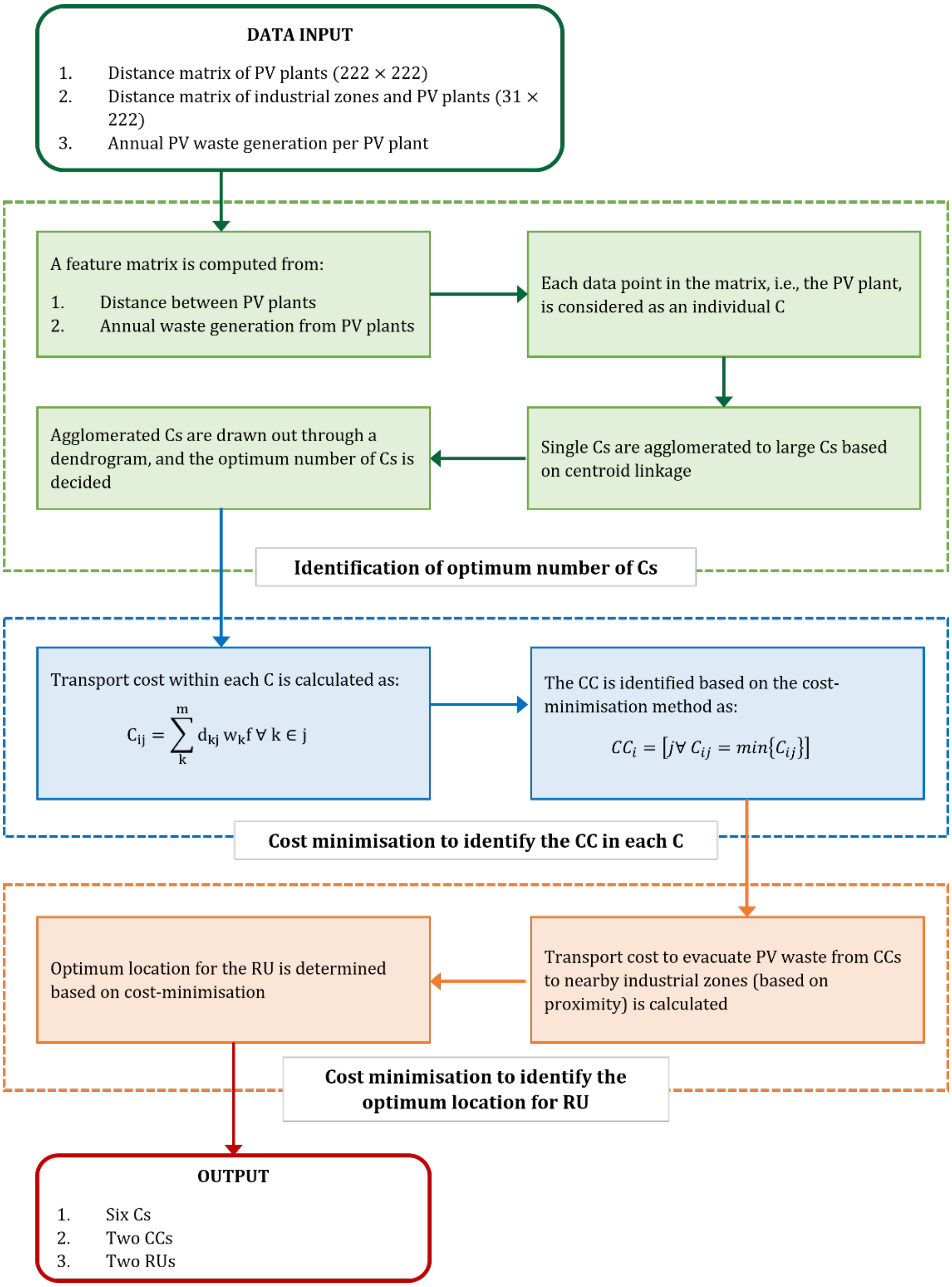
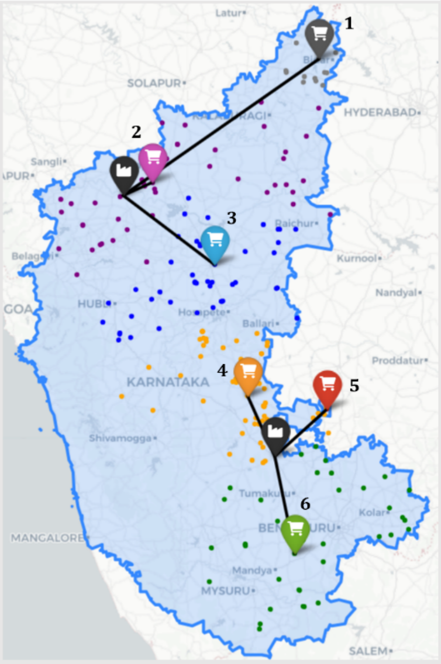


Figure 12: Step-wise guide on AHC

Approach 3 identified '6 Cs, 6 CCs, and 2 RUs' (Figure 13).



Identified districts for CCs, optimal locations for RUs, and estimated EOL PV waste			
S.No.	**CC districts**	**Potential RU zones**	**Total EOL PV waste collected in Cs (in tonnes)**
1	Bidar		39
2	Vijaypura	Vijaypura	98
3	Koppal		99
4	Chitadurga		161
5	Tumakuru	Tumakuru	200
6	Ramanagara		75

Collection Centre (CC) Recycling Unit (RU) Solar PV Plant

Figure 13: Findings of Approach 3

4.2.5 Estimated RU capacity

This study also projected the capacity of RUs to plan the nature of budgetary outlay and infrastructure for setting up recycling facilities that will not only recycle the PV waste but also open greater business avenues for off-takers to reuse and repurpose the recycled waste.

To estimate the RU's capacity, this study considered the average of the projected waste generated by 222 PV plants annually over the years. Figure 14 illustrates the capacity requirement of RUs estimated on the basis of the projected waste volumes for the current and future years.

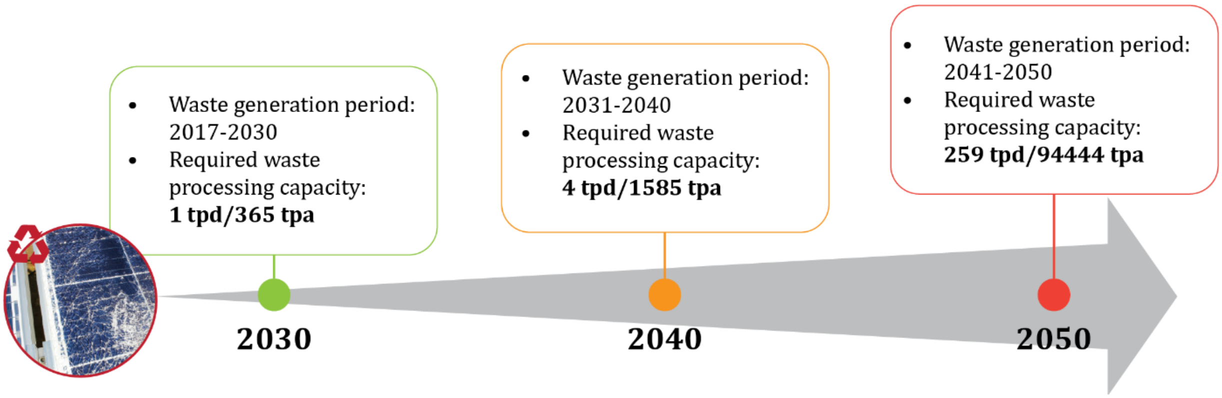


Figure 14: Estimated capacities of the recycling unit in tonnes per day and tonnes per annum, required over the years

The increasing trend in waste generation warrants the need for RUs with a higher recycling capacity. The estimated RU capacity of 1 tonne per day (tpd) for recycling the PV waste generated during 2017–2030 is expected to increase to 260 tpd—an increase of over 250 times—in a business-as-usual scenario during 2041–2050 when most of the 222 PV plants will decommission in Karnataka. However, the optimal size and capacity addition of the RU is contingent upon the nature of technology advancements and investment flows in the country.

5. Discussion

This section focuses on the applicability of the optimisation modelling, the policy recommendations that could enable smooth and quick implementation of the recycling framework, and constructive suggestions for improving investment flows and greater business generation in solar PV waste management in India.

5.1 Comparison of the three approaches

This study evaluated the applicability of the three approaches to make an informed decision concerning their use and feasibility. Because of some underlining differences between the three approaches, their application will depend upon the nature of available datasets and resources.

Table 4: Differentiating characteristics of the three approaches

Optimisation modelling approaches	**Differentiating characteristics**
Approach 1: Installed-capacity-based clustering of PV plants	1. A manual examination approach wherein the number of CCs is left to the judgment and discretion of individuals. 2. Does not take into consideration the dispersion or spread of PV plants other than those with the designated installed capacity. 3. Eliminates the scope of future additions in the installed capacity of PV plants. 4. Because the number of CCs is only dependent on the installed capacity, in cases where the PV plants with the designated installed capacity are higher, this approach may not be ideal to implement. 5. No consideration of transport cost.
Approach 2: Clustering of PV plants on the basis of district-wise cumulative installed capacity	1. A manual examination approach wherein the number of Cs is left to the judgment and discretion of individuals. Outliers could impact the final decision of C formation. In other words, this approach does not ensure polished and refined clustering. For example, in Karnataka, Tumakuru District has a 2-GW PV plant—the largest in the dataset—impacting the overall capacity distribution across the Cs. Moreover, the CCs and RUs in central and southern Cs appear to be near each other as per the results generated. This is because, in this approach, the dispersion or geographical distribution of PV plants is not appropriately considered. 2. The spread of Cs may also not be uniform even if the cumulative installed capacities are almost equal due to the existence of outliers. 3. Eliminates the scope of future additions in the installed capacity of PV plants. 4. No consideration of transport costs to identify the optimum locations of RUs.

Approach 3: AHC-based clustering of PV plants	1. A programming algorithm approach in Python wherein distance proximity and waste generation of PV plants are considered to generate Cs. 2. An accurate or almost accurate determination of Cs, represented through a dendrogram. 3. The approach is applicable irrespective of the number of districts or installed capacities of PV plants in a given state. 4. Consideration of transport costs to identify CCs and optimum locations of RUs. 5. Enables the scope of future capacity additions by adjusting the input matrix. 6. Feasibility and applicability of this approach are easier and more scientific than the other two approaches.

The comparison suggests that Approach 3 is holistic and more scientifically driven than the other two approaches, thereby indicating its greater applicability.

5.2 Policy recommendations and interventions

Despite the significant achievements in RE integration and sustainability, the potential crisis of waste accumulation cannot be overlooked. This study has undermentioned key policy recommendations and interventions that could overcome the barriers and enable the smooth implementation of the recycling framework in India.

5.2.1 Availability of a monitoring and reporting system

One of the key policy recommendations is to have in place a robust monitoring and reporting (M&R) system that will track PV installations, as well as report and regulate the amount of PV waste generated, recycled, and reused in the economy, thereby ensuring the circularity of goods and services. Such a system will keep a check on the PV waste generated and recycled, set recycling targets and supervise their fulfilment, and regulate the informal handling of PV waste.

The M&R system could ensure efficient communication and coordination among PV plant operators, CCs, RUs, regulatory bodies, and other relevant agencies. While the operational mechanisms can be worked out with various stakeholders, an M&R system will allow policymakers to allocate resources effectively and implement strategies for recycling and minimising the environmental impact of PV waste. In other words, it will enhance data-driven decision-making and facilitate the identification of potential bottlenecks and opportunities for improvement and business outreach. Figure 15 is an illustrative image of the M&R system that the study has envisioned.

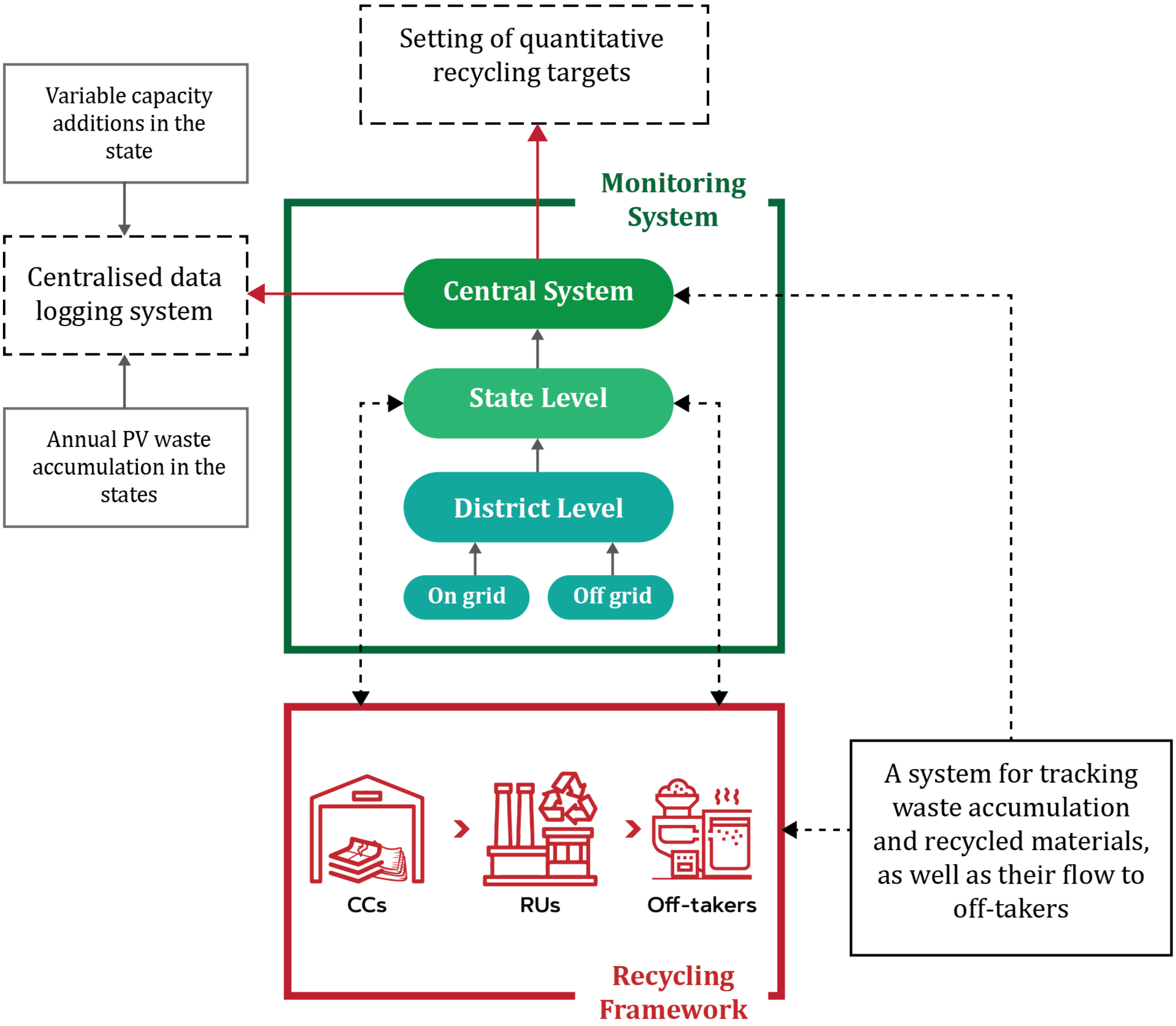


Figure 15: Suggestive M&R system for effective PV waste management in India

A central insurance regulator or a producer responsibility organisation (PRO) could also be useful. The PRO could regulate the waste collection fee (unregulated at present) and the market price of PV panels, impose landfill tax, and cover the producer's or end user's financial losses in case of unforeseen turn of events.

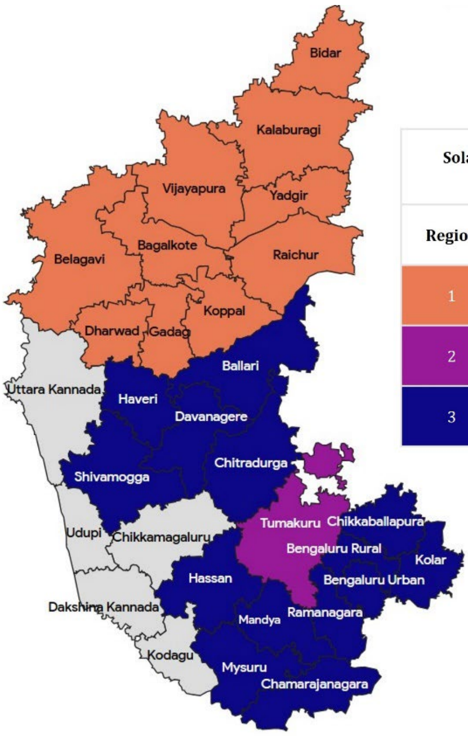
5.2.2 Creation of a special provision for PV waste under e-waste guidelines

Such a provision will help segregate PV waste management from e-waste handling. Moreover, the policy must earmark the producer or agency responsible for the proper management, collection, and recycling of PV waste. It should also set national standards, benchmarks, and rates for waste recycling, apart from enforcing EPR in complete transparency throughout the lifecycle (i.e., from the manufacturing to its EOL) of the PV module. This will ensure that the right owner takes full responsibility for the proper disposal and recycling of PV waste.

5.2.3 Establishment of suitable infrastructure, capitalising untapped potential, and ensuring government licensing systems in place

Consultations with experts indicated the need for a greater number of CCs, especially near or at the site of ground-mounted PV installations. Considering that India's e-waste regulations mandate operators to store failed panels within their premises for an additional 10 years, the need for such centres is expected to exponentially rise in the future. The existence of CCs can be ensured by incorporating their need in the policy, especially the need for solar PV parks. One can also consider capitalising on the untapped potential in a state for solar PV installations, CCs, or RUs.

For example, this study evaluated Karnataka's wasteland and projected the state's untapped potential as >20 GW that could be harnessed as additional solar PV capacity (Figure 16).



Solar potential (tapped and untapped) of different regions in Karnataka		
Region	Tapped Solar Potential (MW)	Untapped Solar Potential (MW)
1	2237	9272
2	2418	-
3	2082	12644

Figure 16: Regions identified to showcase the solar potential (tapped and untapped) of Karnataka

This also necessitates that the producers, waste collectors, and recycling or repurposing agents have a proper government license to function. This will limit the growth of the informal market and enable the formation of a more organised market in solar PV waste handling.

5.2.4 Provision of favourable incentives, funding, and investment-friendly schemes

Incentivising the development of new PV technologies and domestic manufacturing of PV panels through regulatory incentives, infrastructure facilities, guidance from global peers, and adequate funding support is essential to strengthening the circular economy in PV waste management. Moreover, the provision of attractive pricing mechanisms for manufacturers and producers handling PV waste, funding opportunities for R&D programmes, market-based schemes to encourage start-ups in solar PV waste management, etc., could prove beneficial in promoting R&D, businesses, investments, and employment.

5.2.5 Strengthening interlinkages between government, industry, civil society, and the academia

Regular engagements, discussions, and discourses among the relevant stakeholders are critical for developing sustainable solar PV waste management policies and practices. Essentially, collaborations or collaborative initiatives (such as consortiums) between the government and industry are crucial to developing effective EPR policy instruments, including product take-back responsibility, product taxes, collection fees, disposal fees, and minimum recycling requirements. Moreover, awareness campaigns, sensitisation initiatives, and skill enhancement programmes should be conducted to educate the masses about appropriate waste disposal practices and the need for ensuring circularity in goods and services.

5.3 Suggestions for business expansion and investment promotion

Consultations with industry experts indicated that over 90% of the PV panel components are recyclable, thereby opening possibilities for commercial recycling of EOL PV panels in India.

Therefore, the implementation of a comprehensive recycling mechanism is imperative as it will not only facilitate resource recovery but also reduce India's dependency on imports of PV raw materials.

Improving the commercialisation of the solar PV industry will open avenues for off-takers to expand their businesses and outreach to reuse and repurpose recycled PV waste. In any case, the solar PV industry majorly involves business-to-business scenarios. Therefore, greater business opportunities could encourage the industry and off-takers to invest proactively, thereby bringing investments in solar PV waste management, minimising the carbon footprint from such waste, and ensuring circularity in goods and services.

Apart from these initiatives, R&D activities should be strengthened. Initiatives for the development of manufacturing technologies will promote domestic manufacturing, while those focusing on advanced technologies and processes for PV waste recovery will facilitate the effective recycling of PV waste and enable efficient recovery of low- and high-value materials. Research programmes should also be conducted to evaluate and introduce multijunction PV technology and innovative recycling techniques.

For example, combining silicon or thin film with organic materials, such as perovskite, could lead to the development of next-generation or high-efficiency PV modules that are more environmentally safe. Similarly, segregation and separation techniques during the recycling process could help recover or extract high-value materials, such as silicon, that can be reused in the production of new PV panels.

Finally, partnerships and collaborations, through national and international consortiums or technology exchanges could go a long way in promoting efficient waste management practices in the sector.

6. Conclusions

India is expected to generate a considerable amount of solar PV waste in the next two decades. While the guidelines on the overall PV waste handling have been laid out by the Government of India in 2022, clear plans and strategies for recycling and repurposing PV waste remain to be formulated. Currently, approximately 80% of PV waste is being handled informally. Moreover, the absence of standardised recycling benchmarks, limited R&D, inadequate investment incentives, and insufficient capacity-building efforts pose hindrances to ensuring circularity in solar PV waste management.

To overcome these challenges, this study has put together a comprehensive recycling framework for effective PV waste recycling, which could be implemented across India depending upon the nature and quantum of PV waste generated in the future. Moreover, this study opens avenues for more research in this field, especially in examining the feasibility of the recycling mechanism from socioeconomic and environmental aspects.

This study recommends developing a holistic M&R system and partnerships and engagements among relevant stakeholders. By prioritising the implementation of an M&R system, fostering collaboration among stakeholders, improving the commercialisation of the PV waste market, and running awareness cum skill enhancement campaigns, India can regulate this market, significantly reduce informal practices, and lay the foundation for a robust and sustainable PV waste recycling network.

These initiatives will help address the imminent waste management challenge, mitigate the adverse environmental and health effects, and create better employment opportunities. Eventually, the circular economy principles in solar PV waste management will be met, leading to the long-term viability of the solar PV industry in India.

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CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Bengaluru
#18, 10th Cross, Mayura Street, Papanna Layout,
Nagashettyhalli, RMV II Stage, Bengaluru 560094
Karnataka (India)
Noida
1st Floor, Tower-A, Smartworks Corporate Park, Sector 125,
Noida 201303, Uttar Pradesh (India)

www.cstep.in | +91-8066902500 | cpe@cstep.in | @cstep_India