INTER IIT TECH MEET 13.0

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Solar Panel Recycling Challenges: **Prediction And Solutions**

Team **67**

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Problem at a Glance

India is on track to become a global leader in solar energy, with ambitious plans to achieve **500 GW** of renewable energy capacity by **2030**. However, the rapid expansion of solar installations brings a critical challenge: managing the waste generated by **end-of-life solar panels**. With a typical lifespan of **25-30 years**, millions of solar panels installed today will soon reach the end of their operational life, leading to a surge in solar panel waste.

TOXIC

Improper disposal can release toxic substances like cadmium and lead, contaminating soil and water.

India's existing recycling infrastructure is insufficient, particularly in rural and remote areas where many solar panels are deployed.

Valuable resources such as silicon, silver, and copper are often lost due to inefficient recycling methods.

There is limited public awareness and a lack of comprehensive policies to regulate solar panel recycling, further exacerbating the issue.

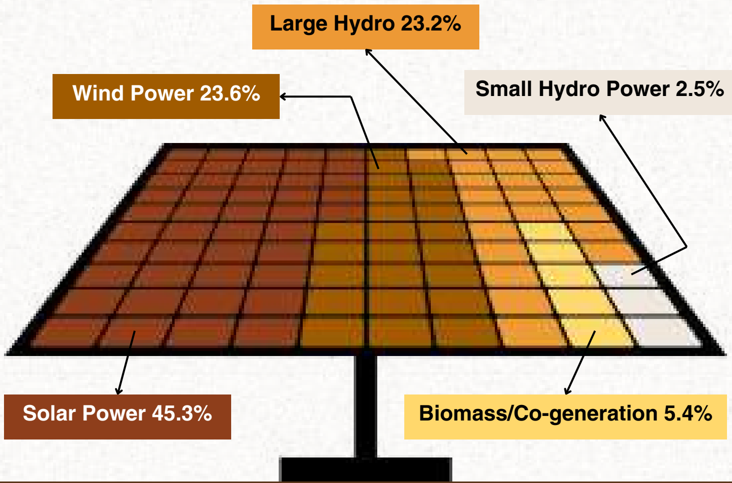
Without an effective waste management strategy, the sustainability of India's solar energy future is at risk. Addressing these challenges is crucial to ensure environmental protection, resource conservation, and long-term energy sustainability.

Objective

The objective of this project is to develop a **scalable**, **cost-effective**, and **sustainable** framework for solar panel recycling in India. Specifically, the project will:

- Predict future solar panel waste volumes based on installation trends and panel lifespan.
- Identify gaps in the current recycling infrastructure and propose solutions to enhance efficiency, scalability, and cost-effectiveness.
- Assess environmental risks posed by improper disposal and explore opportunities for resource recovery.
- Explore innovative recycling technologies and decentralized solutions suited to India's socio-economic conditions.
- Recommend policy measures to promote a circular economy, incentivize recycling, and foster collaboration among stakeholders.

Ultimately, the project aims to make solar energy truly sustainable by reducing waste, conserving resources, and minimizing environmental impact throughout the lifecycle of solar panels.



Current Scenario

India has emerged as the third-largest producer of solar power globally in 2024, following China and the United States. The country has achieved remarkable milestones in solar energy production, boasting a diversified solar panel distribution networks with an installed solar power capacity of **92.12 GWAC** as of October, 2024.

Distribution of Solar Panel Network in India

Large-Scale Solar Parks

India is home to some of the world's largest solar parks. Nearly 70 solar parks have been established across the country to promote large-scale grid-connected solar plants.

Rooftop Solar Systems

As of June 2023, 10.37 GW of rooftop solar (RTS) capacity was installed, part of a total of 55.3 GW for all solar projects in India.

Off-Grid Solar Systems

Off-grid solar systems have been vital in electrifying rural areas with limited grid access, achieving 478 MW installed capacity across three phases (2010–2021)

Grid-Connected Solar Systems

India's solar capacity is dominated by grid-connected systems, with 70.10 GW installed by June 2023, including 57.22 GW ground-mounted and 10.37 GW rooftop systems.

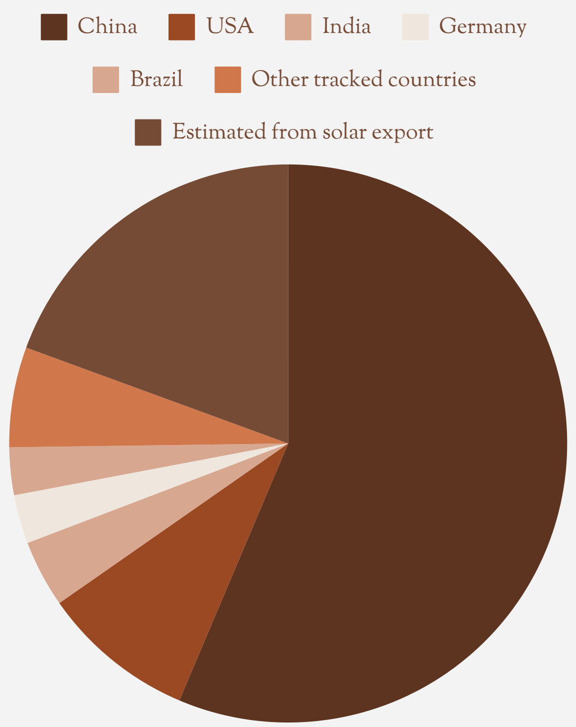


Fig: Global Solar Power Capacity by Country

Regional Disparities

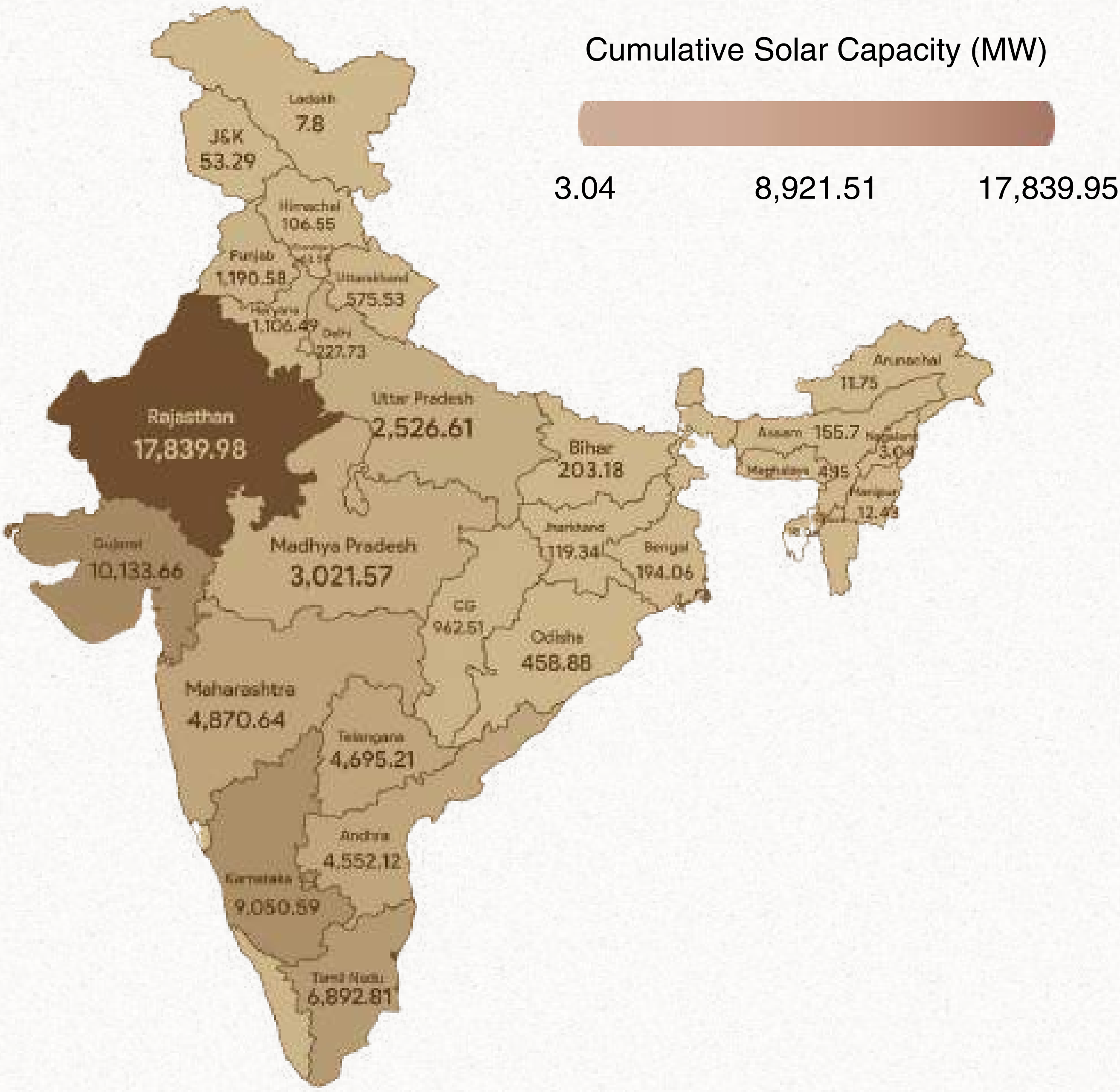
Approximately **90%** of India's solar PV capacity is concentrated in **nine states**, including Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra, which are leading contributors., highlighting the need for regional diversification to enhance grid resilience and broader access to solar energy.

India's Solar Potential

According to the National Institute of Solar Energy (NISE), India's total solar potential is 748 GW, leveraging 3% of its wasteland area. This aligns with India's Nationally Determined Contributions (NDCs) to achieve 50% of power capacity from non-fossil fuels by 2030.

Current Status - Total Renewable Energy capacity of 190.57 GW, with 143.64 GW from solar power, with Solar Energy Generation of 359.89 billion units (BU), marking a 265.89% increase since 2014-15.

Future Scenario - Aiming to achieve 500 GW of renewable energy capacity, with a projected annual waste exceeding 0.5 million tons by 2030.



Data Driven Model for predicting solar panel waste in India

The model predicts future solar panel installations using historical data from **2009 to 2024** with a polynomial regression technique. It then estimates the amount of waste these panels might produce through four main ways: damage during **transport and handling**, wear and tear **during use**, disposal when **panels drop below 80% efficiency (End of Life)**, and **early failures** based on Weibull distribution. It also considers realistic factors like limits on yearly growth, material properties, and how panels degrade over time. The model gives detailed yearly and total waste forecasts, helping the solar industry prepare for recycling, manage waste, and reduce environmental impact.

Key Assumptions:

- **Transport Handling Coefficient (0.2%):** Represents expected damage during shipping, loading/unloading, and installation. Based on industry data showing approximately 1 in 500 panels suffer damage. Includes: Micro-cracks from vibration, Edge damage from handling, Glass breakage during installation, Frame damage during mounting.

- **Project Operation Coefficient (0.5%):** Annual rate of panel damage during normal operation. Accounts for: weather damage (hail, wind, snow loads), maintenance-related damage, hot spot formation, delamination, connection/wiring issues.

- **Mass per MW (65 tons/MW):** Industry standard conversion rate. Typical 400W panel weighs ~20-22kg.

- **Base Degradation Rate (1.4%):** Annual efficiency loss under normal conditions.

- **EOL Efficiency Threshold (80%):** Industry standard for panel replacement. Represents point where energy production becomes economically suboptimal, warranty typically expires, land use efficiency decreases significantly, operating costs exceed benefits.

Input Parameters

Solar Panel Installation Data for India

Year	Installed Capacity (in MW)
2009	100
2010	161
2011	461
2012	1205
2013	2319
2014	2632
2015	3744
2016	6763
2017	12289
2018	21651
2019	28181
2020	34627
2021	40085
2022	56951
2023	66781
2024	81813

Estimating solar panel installation from 2025-2050 in India

To forecast solar panel installations in India, polynomial regression was applied to historical installation data from 2009 to 2024 to project installations for the period 2025–2050. Polynomial models of degree 2 and 3 were evaluated, and the model with the minimal error was selected for the final prediction.

Description of Model:

i) Uses polynomial of degrees 2 and 3:

- **Degree 2**: Captures basic non linear trends (ax +bx+c)
- **Degree 3**: Handles More complex patterns in input/training data (ax +bx +cx+d)

ii) Scales years to a smaller range by subtracting the minimum year to reduce numerical errors.

iii) Applies constraints to limit unrealistic growth or decline:

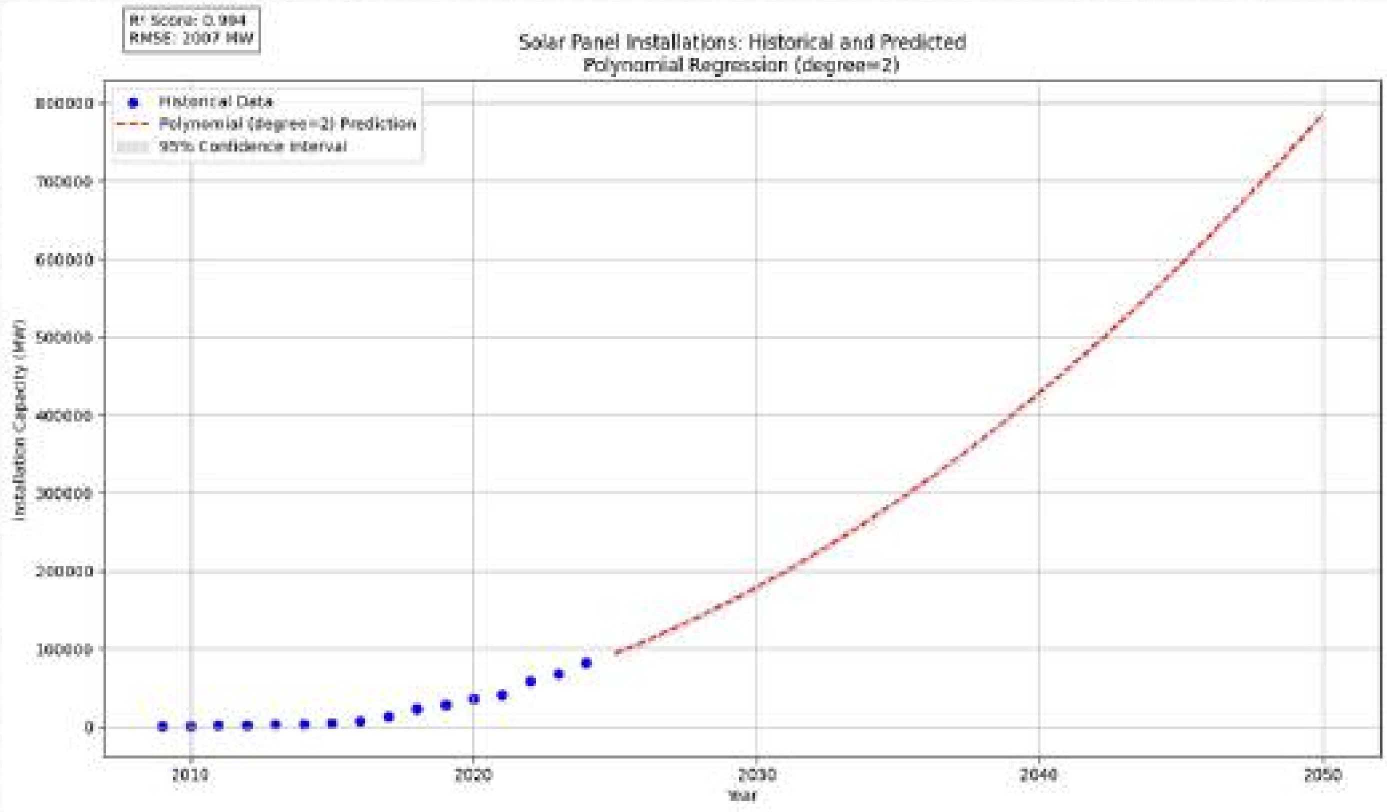
- **Maximum Growth**: 50% of the previous year's capacity.
  - The maximum growth constraint of 50% is based on real-world limitations of the solar industry, encompassing **manufacturing capacity constraints**, **available workforce for installations**, and **grid infrastructure adaptation capabilities.** This ceiling prevents unrealistic growth projections while reflecting actual industry expansion potential.
- **Minimum Growth**: 20% decline compared to the previous year.
  - The minimum decline limit of 20% accounts for the industry's stability factors, including **existing policy support, ongoing project commitments**, and **established infrastructure investments.** This floor acknowledges that the solar market, once established, has significant momentum that prevents rapid decline, even during market downturns.

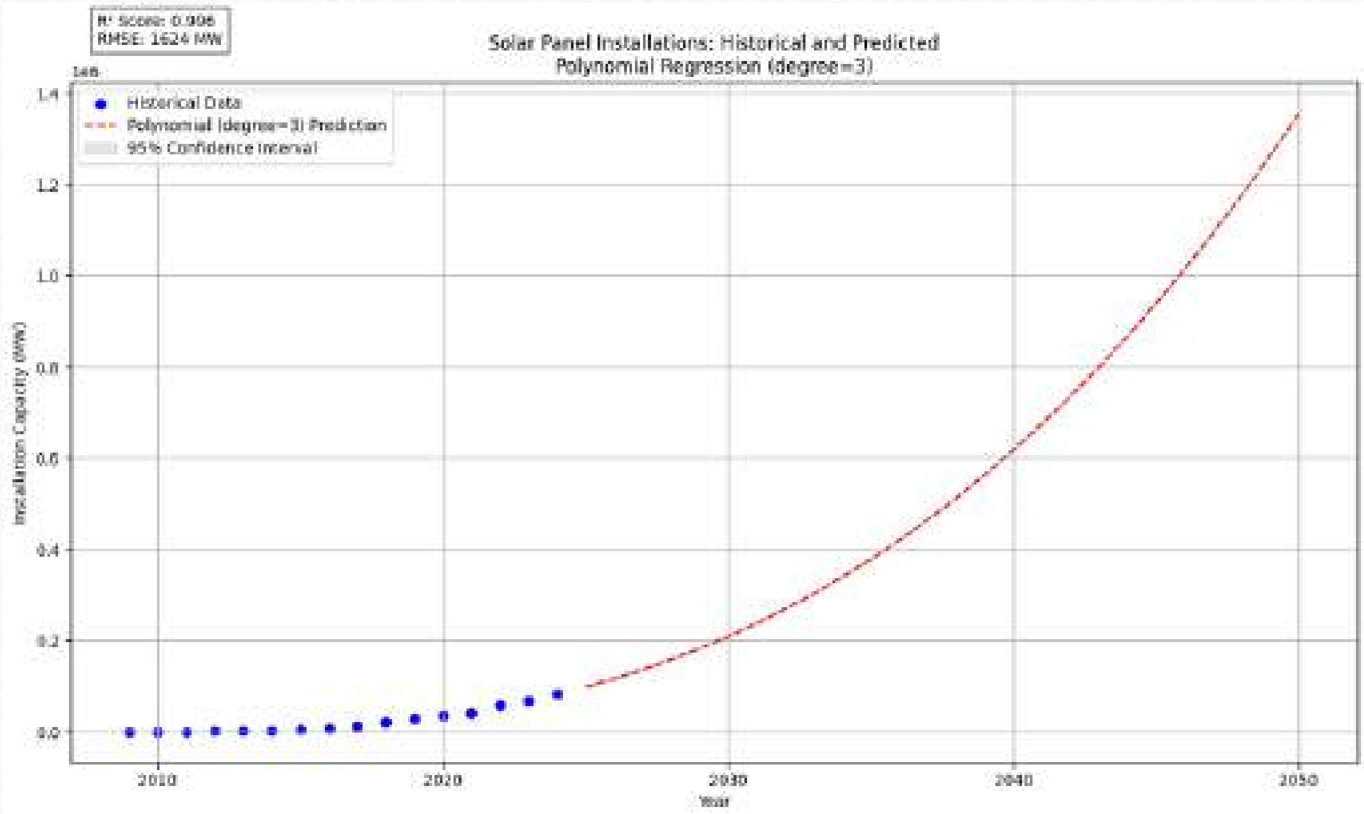
iv) Performance Metrics:

- **R2 Score**: Indicates Goodness of fit
- **RMSE** (Root Mean Squared Error): Quantifies the average prediction error

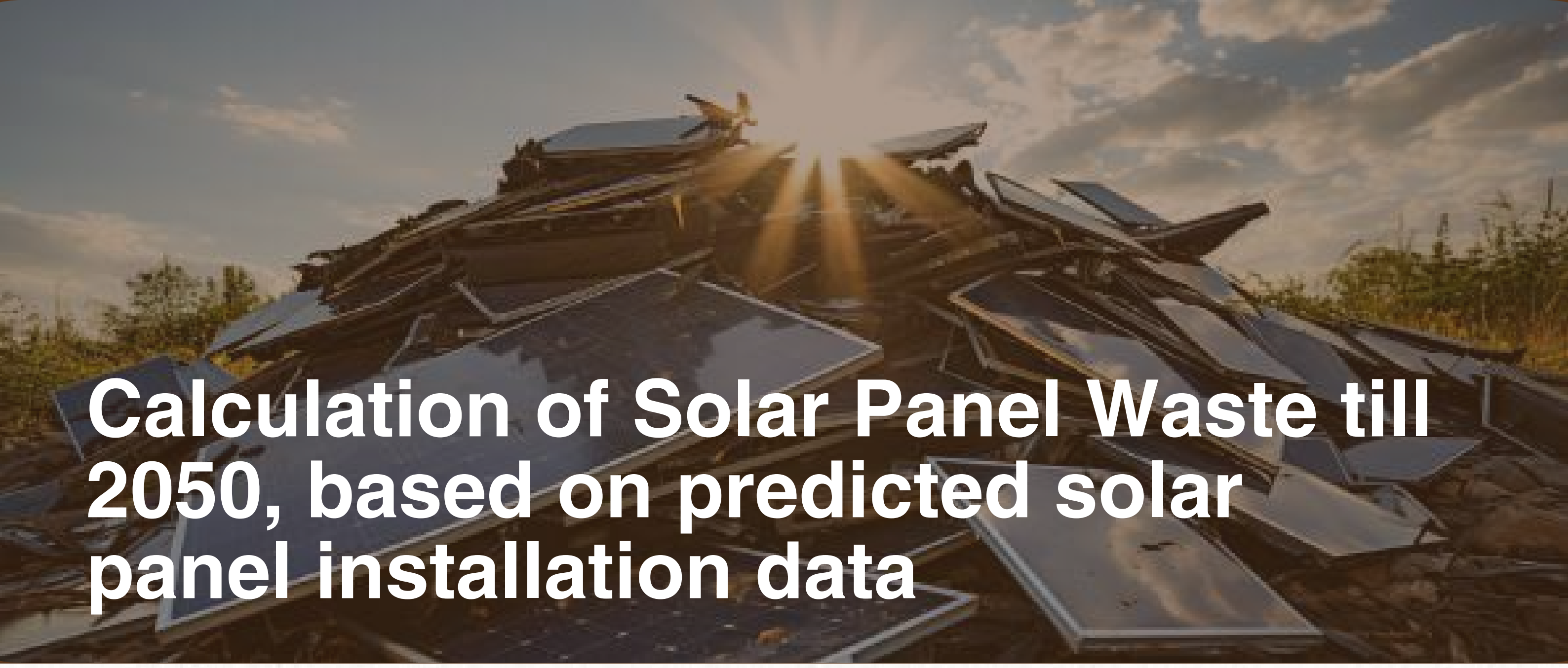
v) Plots data with 95% confidence intervals, using standard deviation on residuals.

Results:





The optimal model selected is a polynomial regression of **degree 3**, as it achieved the **lowest Root Mean Squared Error (RMSE)**.



Calculation of Solar Panel Waste till 2050, based on predicted solar panel installation data

- Assumptions for waste generated due to End of Life (EoL) of Panel:
  - Starts at 100% efficiency.
  - Threshold at 80% efficiency, meaning a solar panel is considered to have reached its End of Life (EoL) when its efficiency falls below this level.
  - Considering annual degradation rate is 1.4% of efficiency annually.
  - Additionally, the annual degradation rate is assumed to decrease at five-year intervals, with the current annual degradation rate being divided by 1.01 at each interval. This adjustment accounts for technological advancements that are expected to enhance efficiency over time.

- Waste generated due to transportation and handling:
  = Installation_capacity(in MW) * mass_to_MW * transpot_handling_coefficient

  mass_to_MW= 65 tonnes per MW
  transport_handling_coefficient= 0.002 (0.2%)

- Waste generated due to Operational loss:
  = Installation_capacity(in MW) * mass_to_MW * operational_loss_coefficient

  mass_to_MW= 65 tonnes per MW
  transport_handling_coefficient= 0.005 (0.5%)

- Waste generated due to Early Failure before EoL (**Weibull distribution**):

  The Weibull function is a statistical model commonly used to describe the probability of failure of solar panels over time. It is particularly effective for modeling early failures and degradation patterns due to its flexibility in representing different failure rates.

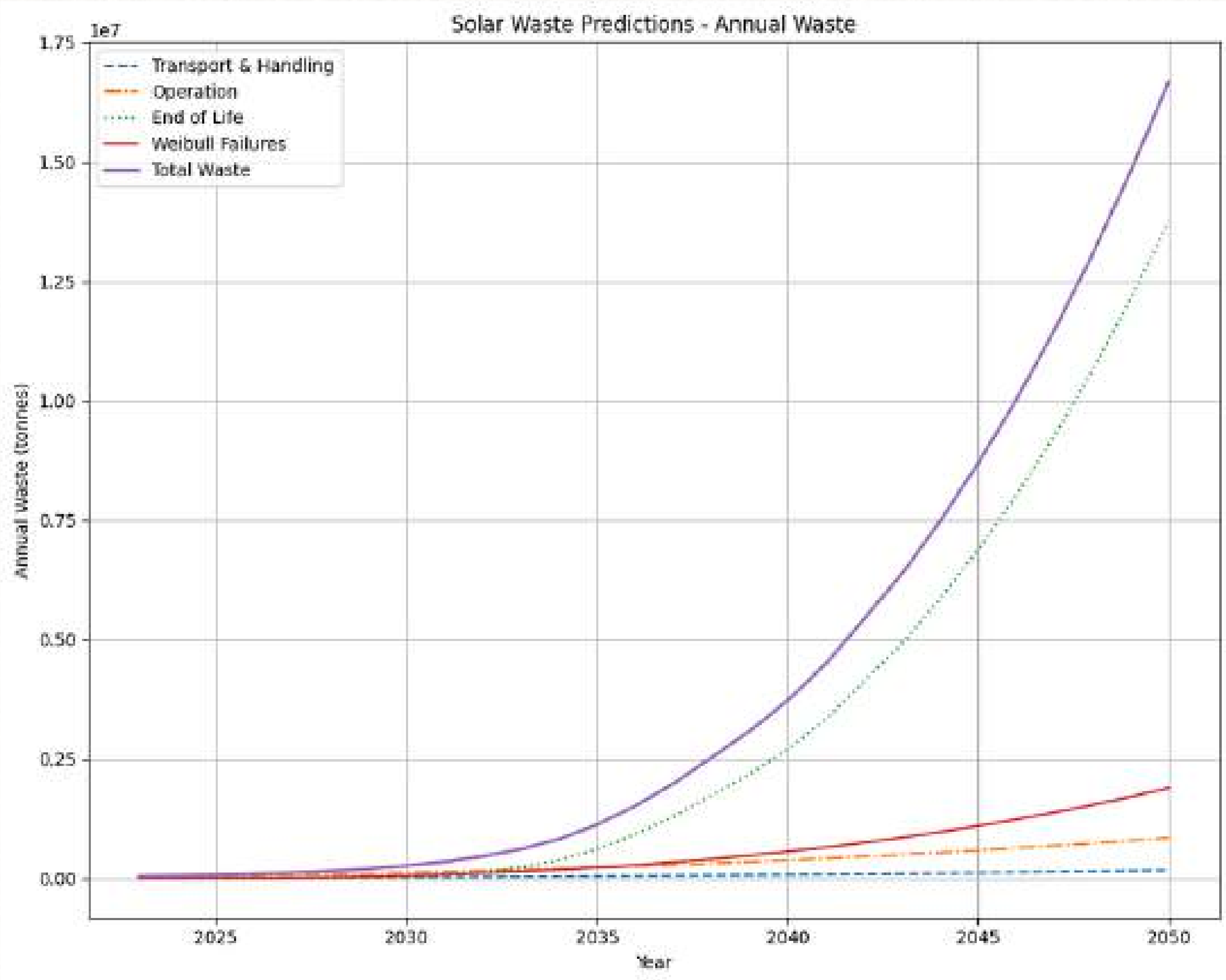
$$F(t) = 1 - \exp\{-(t/\tau)^{\alpha}\}$$

t : time(in years)
τ : 25 years (expected lifetime of solar cell)
α : 5.37 (shape parameter, controls failure rate pattern)*
$F(t)$ gives failure probability

Weibull Waste = Installation_capacity * mass_to_MW * Failure_probability(F(t))

Total Waste generated in a year** = Waste due to End of Life + Waste due to Early Failure (Weibull distribution) + Waste due to transportation loss + Waste due to operational loss

Results:



*For details about weibull function refer appendix
**Code for waste calculation is in appendix

Solar Waste Predictions - Annual Waste

2030 Total Waste: 2,68,358.3 tonnes
2050 Total Waste: 1,66,81,999.8 tonnes

Environmental Impact

Environmental Risks of Improper Solar Disposal

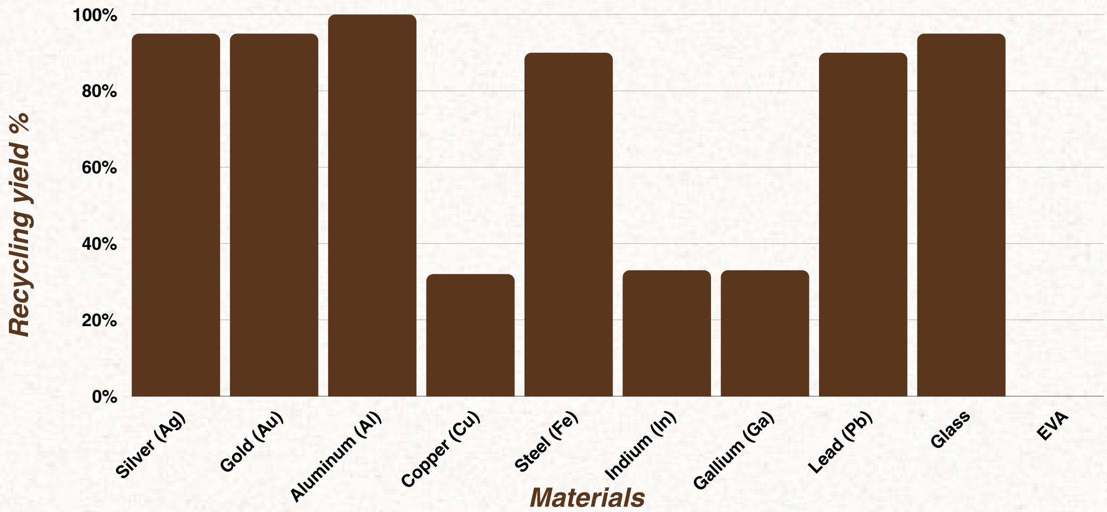
- **Heavy Metal Contamination:** Solar panels contain toxic materials like lead, cadmium, and selenium, which can leach into soil and groundwater if panels are not disposed of properly.
- **Soil and Water Pollution:** The glass and polymer components of solar panels can degrade over time, releasing microplastics and other pollutants into the environment. These materials can persist for decades, polluting soil and water sources.
- **Greenhouse Gas Emissions:** If solar panels are incinerated instead of recycled, they release greenhouse gases and other harmful compounds, counteracting the environmental benefits of solar energy.
- **Increased Landfill Burden:** Solar panels are bulky and take up significant space in landfills, exacerbating the growing issue of electronic waste and reducing available landfill capacity for other waste streams.
- **Harm to Biodiversity:** Toxic leachates and microplastics from discarded panels can harm plants, animals, and microorganisms, disrupting local biodiversity and ecosystems

Short-term mitigation strategies

- Promoting **safe and temporary storage** of EOL solar panels at designated facilities to prevent immediate environmental harm
- Setting up **local collection points** to gather EOL panels for **centralized handling**, **minimizing improper disposal**
- Collaborate with NGOs, local governments, and waste management companies to streamline short-term disposal and recycling processes
- **Educating about the risks** of improper disposal and the importance of recycling, emphasizing the available resources
- **Strengthening enforcement** of existing e-waste and hazardous material disposal regulations to include solar panels

Assessment: The environmental risks posed by the improper disposal or non-recycling of solar panels, including the release of harmful chemicals such as cadmium, lead and other toxic by-products that can contaminate ecosystem could be assessed by above observations.

Key materials in solar panels that could be reclaimed, such as silicon, silver, and copper, and assess their potential economic value if recovered effectively.



Resource Recovery from Solar Panel Materials

Category	Material	Cost (USD/tonne)	Primary Usage	Economic Potential
Precious Metals	Silver (Ag)	$651,000	Si-based solar panels	High
	Gold (Au)	$49,375,000	Inverters	Extremely High
Base Metals	Aluminum (Al)	$2,000	Structural components, frames	High
	Copper (Cu)	$9,646	Cabling	Moderate
	Steel (Fe)	$600	Structural and mounting	Moderate
Critical Metals	Indium (In)	$460,000	CIGS panels	High
	Gallium (Ga)	$290,500	CIGS panels	High
Toxic Metals	Lead (Pb)	$2,320	Soldering, connectors	Moderate
Bulk Materials	Glass	$790	Cover and structural layers	Low (high volume)
	EVA	Low Value	Encapsulation material	Low

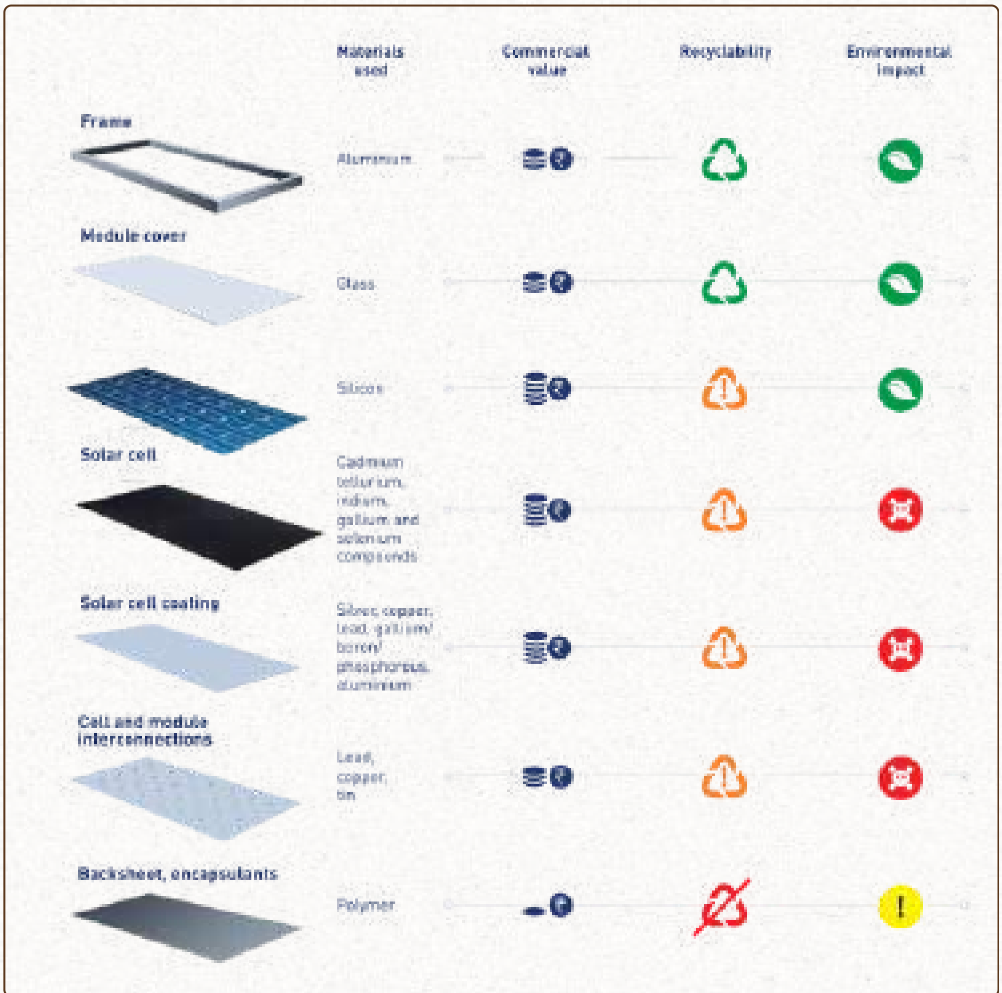


Fig : Solar module composition and waste classification

Solar Waste Collection: Insights, Challenges, and Recommendations

With India's solar sector growth, managing end-of-life (EOL) solar panels has become a critical challenge. Efficient solar waste collection is essential to prevent environmental hazards, optimize recycling, and establish a sustainable solar economy—necessitating a closer look at collection practices globally and their relevance to India.

Current Scenario in India

The current solar PV waste collection in India is dominated by the **informal sector**, which often ends up leading to improper disposal especially as landfills. A very minimal part of the waste, like the aluminum panel gets recovered since it is easier to separate and is cheap which encourages the informal collectors to simply extract the frame and dispose the rest of the panel without any further recycling and measures.

1. **Status and Volume:**
    - India has over 92 GW of installed solar capacity (as of 2024), with waste projected to rise from 340,000 tons by 2030 to 2 million tons by 2050.
    - Key Contributors: Five states; Rajasthan, Gujarat, Karnataka, Andhra Pradesh, and Tamil Nadu will generate 67% of solar waste by 2030.
2. **Regulatory Framework:**
    - Solar cells and modules are covered under the Electronic Waste (Management) Rules, 2022, but enforcement and compliance remain limited.
    - Lack of Extended Producer Responsibility (EPR) mandates delays the establishment of robust collection infrastructure.
3. **Collection Infrastructure:**
    - Fragmented efforts with no national framework for collection points or systematic disposal.
    - Logistical challenges in rural and remote installations.
4. **Lack of Awareness:**
    - Many stakeholders, including consumers and smaller manufacturers, remain unaware of disposal requirements, causing panels to accumulate in landfills or abandoned sites.
5. **Economic Constraints:**
    - Collection costs are high, especially for remote area installations, deterring businesses from establishing formal collection systems.

India's solar PV waste management faces significant challenges due to informal sector dominance, weak enforcement of regulations, lack of EPR mandates, and high collection costs.

Global Scenario

European Union (EU)

Classified under the WEEE directive, which mandates producers to finance collection and recycling **(EPR)**

Successes:
High collection rates (~70% of EOL panels)

Challenges:
High logistical costs.

United States (US)

Solar panels fall under general waste laws with no federal mandates. State-specific initiatives exists that regulate disposal

Successes:
No notable achievements
Challenges:
Lack of **federal-level standards** leads to fragmented efforts & low collection efficiency

Japan

Consumer-Driven Model with Incentives to return EOL panels. Panels are not categorized under e-waste, but recycling initiatives exist.

Successes:
High material recovery rates.
Challenges:
Absence of a unified legal framework limits scalability.

China

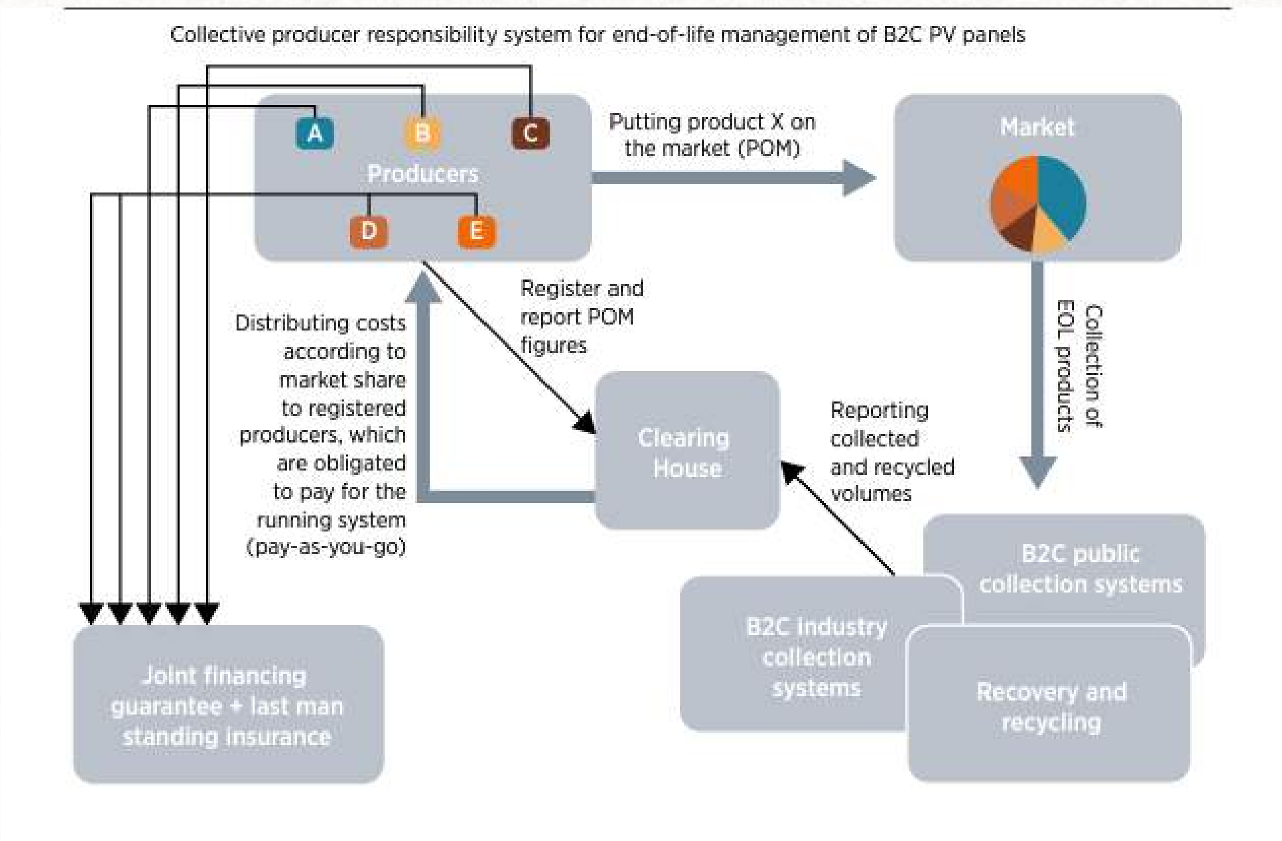
Centralized collection systems supported by state-owned enterprises. Focus on **volume-based recycling** with government subsidies and framework.

Successes:
No notable achievements
Challenges:
Cost-cutting in collection leads to **improper disposal** and lower recycling standards.

Comparative Analysis: Global Models vs. Indian Context

Aspect	EU	Japan	USA	India
Regulatory Strength	High (WEEE Directive)	Moderate	Weak	Evolving
Economic Viability	Expensive	Moderate	High-cost, low efficiency	Limited funding
Logistical Feasibility	Strong infrastructure	Urban-focused	Scattered	Fragmented
Socioeconomic Fit	High consumer awareness	Tech-savvy urban centers	Limited alignment	Diverse demographics, low awareness

Successful Collection Model Observed from Global Nations



Transportation of Solar Waste

Now that we have examined the various collection practices for solar panel waste across multiple nations, it is equally crucial to explore the transportation processes that bridge the gap between collection points and recycling centers. Efficient transportation is vital for ensuring that the collected waste is delivered to recycling facilities in a cost-effective, timely, and environmentally sustainable manner.

Before diving into the transportation models, it is important to understand the challenges faced in India for the solar panel waste transportation to better understand the situation and devise a better strategy to address the issue.

Geographical Diversity
Vast distances and diverse terrains complicate solar waste transportation logistics

Economic Constraints
High costs and low return on investment

Dispersed Waste Generation
Fragmented across small and medium-scale installations

Environmental Impact
Contributes to greenhouse gas emissions challenging ultimate motive

Infrastructure Deficits
Lack of transportation infrastructure creates bottlenecks in waste collection

Low Waste Volumes
Dispersed waste generation makes centralized transportation uneconomical

Regulatory Gaps
Absence of clear guidelines hinder planning and execution

Seasonal Accessibility
Monsoons and extreme weather conditions can hinder transportation

Challenges in Solar Panel Waste Transportation in India

Models for Solar Panel Waste: Transportation and Logistics

To address the challenge of transporting solar panel waste efficiently, several models that have been implemented globally, each suited to different geographical, economic, and logistical conditions are studied. These models serve as the foundation for designing an optimal system suited to India's unique socioeconomic & infrastructural conditions, enabling an effective and scalable solution for solar panel recycling. Below, we discuss key transportation and collection models, their features, operational flows, examples of countries adopting them, and their applicability to the Indian context.

Decentralized Model

The decentralized model establishes multiple small-scale collection and preprocessing centers near waste generation points. These centers focus on collecting, segregating, and preprocessing solar panel waste locally before transporting it to central recycling facilities.

Key Features

- Localized infra to minimize transport.
- Facilities to dismantle & segregate waste at the collection centers.
- Focus on creating a network of smaller, scalable facilities.

Operational Flow

- Solar waste is collected from nearby sites.
- Centers sort, dismantle, and store temporarily.
- Preprocessed materials are sent to centralized plants.

Cost Analysis

- Setup Costs: Moderate, with distributed infrastructure.
- Transportation Costs: Reduced by local preprocessing.
- Operational Costs: Lower for localized centers.

Advantages

- Reduces transportation costs and environmental impact.
- Generates local employment opportunities.
- Effective for regions with a moderate waste density.

Challenges

- Coordination needed between units and facilities.
- Infrastructure costs rise with more centers.
- Managing small waste volumes from scattered locations is hard.

Followed by : Germany France Japan

Mobile Collection and Transportation Model

This model employs mobile collection units equipped to access dispersed or remote locations. These units can carry out basic dismantling and sorting operations at the collection site itself, reducing the need for static infrastructure.

Key Features

- Mobility allows coverage of geographically dispersed areas.
- On-site preprocessing to reduce transportation volume.
- Flexibility in addressing regions with unpredictable/low waste generation.

Operational Flow

- Mobile units are dispatched to waste generation sites based on a pre-set route or demand.
- Panels are dismantled, sorted, and sent to centralized recycling facilities to optimize transport.

Cost Analysis

- Setup Costs: High due to specialized vehicles/equipment.
- Transportation Costs: Moderate as volume is reduced on-site.
- Operational Costs: Higher due to fuel and staffing expenses.

Advantages

- Reaches remote areas with low population density.
- Reduces need for permanent infra in remote areas.
- Adaptable to regions with variable waste generation.

Challenges

- Limited capacity per trip can lead to frequent deployments.
- High operational costs for maintenance and staffing.
- Logistical complexities in scheduling and routing.

Followed by : Sweden Australia

Some countries have successfully combined decentralized, mobile, and centralized models to address the diverse challenges of e-waste management. For instance, **Norway** integrates mobile units with regional hubs to optimize e-waste collection and transportation. Drawing on these experiences, a **hybrid model** for India could be formulated to adapt to its unique socioeconomic and geographical diversity for solar waste management.

Centralized Model

In the centralized model, waste is collected from various locations and transported directly to a large recycling facility. This approach focuses on economies of scale and centralizes high-capacity processing in one location.

Key Features

- One Single, large-capacity recycling plant.
- Bulk transportation of waste to central facilities.
- Efficient handling of large volumes of waste.

Operational Flow

- Waste is collected from generation sites or regional hubs.
- It is transported directly to a central recycling facility.

Cost Analysis

- Setup Costs: High for the setup of central plant.
- Transportation Costs: High for long-haul transport.
- Operational Costs: Economical due to economies of scale.

Advantages

- High processing efficiency at central facilities.
- Simplified logistics system.
- Suitable for areas with concentrated waste generation.

Challenges

- Expensive transportation over long distances.
- Unsuitable for regions with dispersed waste generation.
- High environmental impact from transportation emissions.

Followed by : United States (US) China

Comparative Analysis of Models

Model	Setup Costs	Transportation Costs	Coverage	Scalability	Global Examples
Decentralized	Moderate	Low	High (Local)	High	Germany, Japan, France
Mobile	High	Moderate	High (Remote Areas)	Moderate	Australia, Sweden
Centralized	High	High	Low (Urban Areas)	Limited	US, China

Limitations of Existing Models in the Indian Context

1. **Geographical Diversity**: Large rural areas with poor connectivity make decentralized and mobile models challenging to scale.
2. **Economic Constraints**: High costs of infrastructure and operations hinder the adoption of centralized or mobile systems in many regions.
3. **Policy Gaps**: Lack of clear solar waste regulations and collection mandates complicates implementation.
4. **Lack of Public Awareness**: Limited awareness about solar panel recycling hampers participation in decentralized and mobile collection initiatives.
5. **Infrastructure Deficits**: Poor transport and waste management infrastructure make centralized models inefficient in rural and semi-urban regions.

India requires a **cost-efficient**, **decentralized**, and **scalable model**, drawing on the strengths of global models while addressing local constraints like its socio-economic conditions, including a large rural population, decentralized installations, and informal recycling practices that leads us to a hybrid approach.

Proposed Model with Decentralized Recycling Units:

Localized Recycling Units form a critical component of the proposed model, ensuring that waste management strategies are tailored to the needs of urban and rural areas. This approach is designed to address the logistical challenges and inefficiencies currently faced in India due to the country's vast geography, limited infrastructure, and growing solar energy installations.

The focus is on minimizing costs, improving operational efficiency, and enhancing sustainability through reduced environmental impact.

URBAN Scenario

Household Solar Panels and Small Industries

Urban areas are characterized by a mix of household solar panels, solar installations for housing societies, and small to medium industries. The waste generated here is often fragmented and dispersed.

Decentralized Hubs in Urban Areas

- Set up small-scale recycling hubs integrated with existing e-waste collection centers or municipal waste facilities.
- These hubs temporarily store and preprocess dismantled panels to reduce volume and prepare components for centralized recycling.

Transportation Solutions

- Use smaller collection vehicles that can navigate urban areas efficiently.
- Optimize routes through AI-driven algorithms to reduce traffic delays and fuel consumption.

Community-Based Incentives

- **Incentive Models**: Offer monetary rewards or discounts on new panels for proper EOL panel disposal, such as cash incentives, reduced electricity tariffs, tax rebates, or other financial benefits.
- **Public-Private Partnerships** (**PPPs**): Encourage collaboration between municipal bodies and private recycling firms to share infrastructure, reduce costs, and ensure compliance.
- **Leverage CSR funds** from corporations, particularly those benefiting from solar installations, to support collection and recycling.

Integration with Local Entities

- Leverage existing urban waste management infrastructure and e-waste collection networks to set up solar panel collection points.
- Collaborate with **Resident Welfare Associations** (**RWAs**), **industrial zones,** and **development bodies** to streamline solar panel disposal for all types of installations.
- Partner with municipalities to **raise awareness** about EOL solar panel disposal, recycling benefits, and incentives.

RURAL Scenario

Solar Parks for Industries and Government Projects

In rural areas, solar parks are primarily established for large-scale industrial operations and government-led renewable energy initiatives. These installations generate waste in bulk, creating a unique set of challenges and opportunities for effective waste management and recycling.

Centralized Recycling Hubs

- **Central Recycling Unit**: Establish medium to large-scale recycling units near industrial solar parks or in regions with high waste generation volumes.
- **Hub and Spoke Model**: Use a centralized hub model where dismantled materials from surrounding areas are aggregated for large-scale recycling operations.
- **Mobile Dismantling Units**: Deploy mobile units to on-site locations to dismantle panels, reducing transportation costs and ensuring safe handling.

Partnering with local Entities

- Collaborate with **local governance bodies** and grassroots organizations to manage collection points.
- Incorporate cooperative organizations to organize collection and pre-transportation sorting activities, which can also provide employment.
- Conduct **awareness campaigns** through **Panchayats** and local cooperatives about proper disposal practices.
- Provide **training programs** for dismantling, sorting, and preprocessing waste materials.

Reverse Logistics

Leverage **industrial supply chain transportation networks** and adopt cost-effective, eco-friendly multi-modal transport methods, such as **road and rail**, to efficiently move dismantled waste from remote sites to recycling hubs.

Integration with Rural Renewable Energy Programs

- Reuse functioning components from dismantled panels in community solar projects.
- Encourage **hybrid business models** combining solar energy generation and recycling.

Integrated Urban-Rural Workflow

1. **Collection and Segregation:**
   - Urban collection hubs and rural mobile units gather and preprocess solar waste, segregating components for efficient transportation.
2. **Transportation Optimization:**
   - In urban areas, waste is sent directly to decentralized recycling units or consolidated for transport to larger hubs.
   - In rural areas, dismantled waste is transported to centralized hubs using bulk carriers optimized for cost and distance.
3. **Recycling and Material Recovery:**
   - Urban hubs handle simpler recycling tasks (e.g., glass and plastic segregation), while rural hubs focus on industrial-scale recycling.

Sustainability and Scalability

1. **Environmental Benefits:**
   - Urban Areas: Reduces greenhouse gas emissions by minimizing the need for long-distance transportation of fragmented waste.
   - Rural Areas: Mitigates waste accumulation at remote solar parks through localized processing.
2. **Economic Viability:**
   - The decentralized model lowers the upfront investment in transportation infrastructure.
   - Recovered materials from recycling (e.g., silicon, copper, silver) offer significant value, offsetting operational costs.
3. **Scalability:**
   - Pilot projects in high-density urban areas and regions with major solar parks provide data for scaling. A Delhi based case study is attached in appendix.

Role of Digital Technologies in Solar Panel Waste Transport & Management

AI and Machine Learning for Optimization

- Location-Allocation Modeling (LAM): AI identifies optimal dismantling center locations using panel density, geography, and demand data.
- Vehicle Routing Problem (VRP): AI computes efficient routes using real-time traffic, weather, and road condition data.
- Predictive Analytics: Machine learning predicts waste trends based on installation rates, panel lifespans, and seasons.

Benefits: Enhances center placement, route optimization, and waste region identification.

IoT for Real-Time Tracking and Monitoring

- Sensors for Waste Management: IoT devices track truck location (GPS), capacity, and waste condition (damage or hazards).
- Live Data for Routing: Sensors provide real-time updates for route adjustments, addressing traffic, road closures, and weather.
- Enhanced Efficiency: Optimized truck deployment cuts fuel use, downtime, and logistics costs.

Benefits: Better resource use, lower environmental impact, and quicker, safer waste collection.

Blockchain for Transparency and Compliance

- Waste Lifecycle Tracking: Blockchain ensures an immutable record of a solar panel's lifecycle, from collection to recycling and material reuse.
- Building Trust: Guarantees adherence to regulations, enabling audits and boosting trust among stakeholders, consumers, and governments.

Benefits: Enhances compliance, facilitates accountability, and builds confidence in waste management systems.

Digital Platforms for Stakeholder Coordination

- Centralized Portals: Platforms streamline EOL solar panel reporting and tracking, connecting panel owners, recyclers, dismantling centers, and logistics teams.
- Consumer Engagement: Apps allow scheduling pickups and tracking waste processing.
- Operational Efficiency: Improved communication minimizes delays and reduces administrative efforts.

Benefits: Simplified coordination, better user experience, and more efficient operations.

Challenges to current recycling Infra in terms of efficiency, scalability and cost

Challenges in Recycling Efficiency

1. **Recovery Rates & Technologies:** Recovery rates for **silicon (85-90%)**, **glass (88%)**, and **silver/aluminum (80-85%)** are moderate. Mechanical processes can damage materials, thermal processes release harmful emissions, and chemical processes generate hazardous waste and use significant energy.
2. **Pollution:** Thermal treatments (500–600°C) emit **NOx and SO2**, while burning polymer encapsulants releases toxic gases.
3. **Silicon Purity:** Recovery is costly, using methods like nitric acid dissolution (25 hours at 60°C) or thermal decomposition (over 500°C).
4. **Workforce Issues:** India's waste management workforce lacks skills and safety measures for effective PV recycling.
5. **Data Gaps:** Insufficient data on panel types and volumes hinders accurate waste generation forecasts and recycling planning.

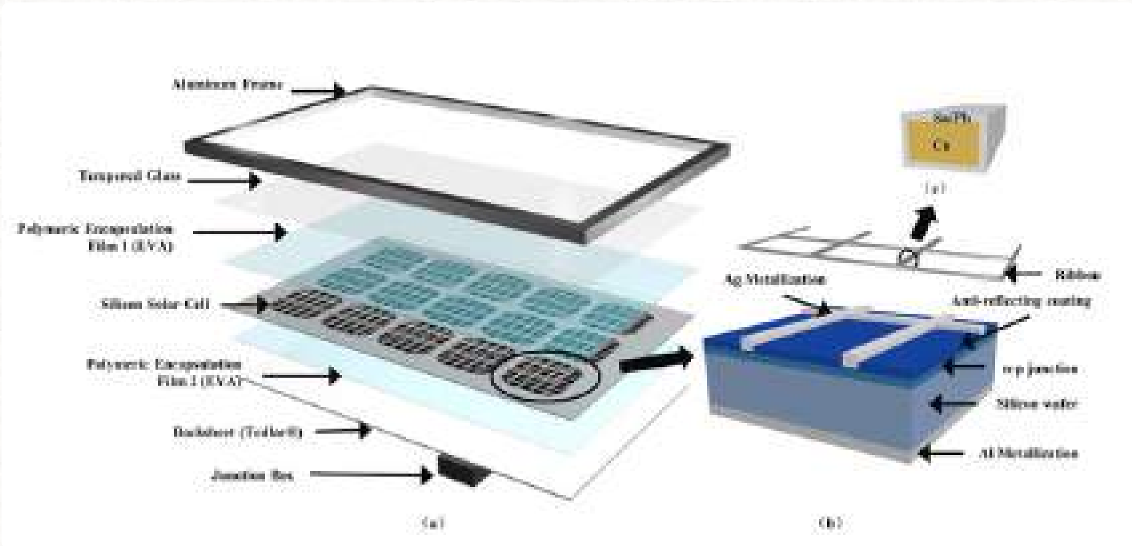
Challenges in Scalability

1. **Volume Growth:** India will generate **4.5–7.5 million tonnes** of PV waste by 2050, but infrastructure scaling has not yet begun.
2. **Small-Scale Efforts:** Projects like SWAP **(2.5 tonnes/day)** are inadequate for expected volumes, and the lack of regional facilities increases transportation needs.
3. **Economic Barriers:** High transport costs **(Rs 400/panel)** dominate recycling expenses, with material recovery accounting for less than **50%** of total costs.
4. **Policy Gaps:** India lacks **Extended Producer Responsibility (EPR)** laws, unlike countries like Germany and Italy.
5. **High Infrastructure Costs:** Setting up large-scale facilities is expensive **($6.72/m² private cost, $5.71/m² external cost)**, discouraging private investment.

Cost Challenges

1. **Transport Costs:** Rooftop systems (40% of India's solar target) increase costs due to scattered distribution. Transport alone can cost **Rs 400/panel**.
2. **Low Recoverable Value:** Recoverable material value often falls **below 50%** of recycling costs, making operations financially unviable.
3. **Market Issues:** Materials like glass, aluminum, and silicon have low resale value relative to recycling and logistics costs.
4. **Technology Viability:** Technologies like pyrolysis and gasification remain commercially unviable due to high operational costs.

Component Analysis of Solar Panel



Assumptions

The following assumptions have been made for this case study:

- C-Si PV Waste Input: The recycling process assumes an input of 1000 kg of crystalline silicon (C-si) PV panel waste. The composition of the PV modules is derived from laboratory tests conducted under the FRELP project (refer to the Table). Each panel weighs approximately 22 kg and covers an area of 1.6 m².

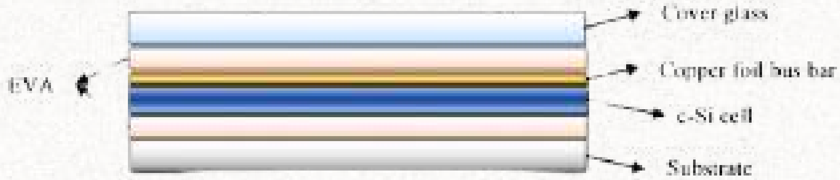
Material	Quantity	Unit	(wt/wt)
Glass, containing antimony (0.01-1 %/kg of glass)	700	kg	70 %
Aluminium frame	180	kg	18 %
Copper connector	10	kg	1 %
Polymer-based adhesive (EVA) encapsulation layer	51	kg	5.1 %
Back-sheet layer (based on polyvinyl fluoride)	15	kg	1.5 %
Silicon metal solar cell	36.5	kg	3.56 %
Silver	0.53	kg	0.053 %
Aluminium, internal conductor	5.3	kg	0.53 %
Copper, internal conductor	1.14	kg	1.14 %
Various metal (tin, lead)	0.53	kg	0.053 %
Total	**1 000**	**kg**	**100 %**

Crystalline-silicon based PV panel

Component Analysis

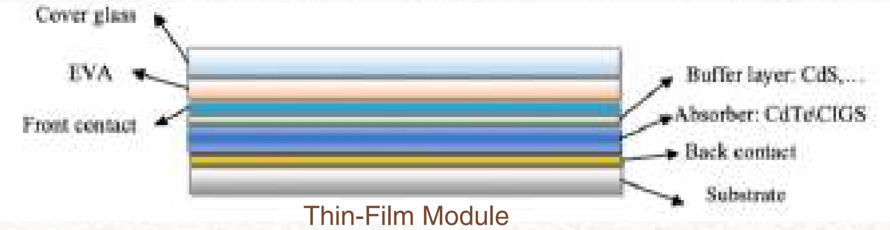
Summary of Key Differences and Trends:

Crystalline Silicon Modules:
These dominate the market, featuring innovations like thinner wafers, sliver cells, and improved production methods. They offer high efficiency, though reducing silicon content to lower costs remains a priority.



Crystalline Si Module

Thin-Film Modules:
While less efficient, these modules are more cost-effective and versatile. Thin-film technologies, particularly CIGS and CdTe, show promising cost reduction potential with increased production. Recent hybrid and sliver technology advances work to improve their efficiency.



Thin-Film Module

Company	SolarWorld	FirstSolar	ANTEC Solar GmbH
PV module type	**c-Si**	**Thin film**	**Thin film**
Technology	• Thermal decomposition • Manual material separation • Etching	• Physical disintegration (shredding + hammer milling) • Leaching • Solid-liquid separation • Vibrating screening • Precipitation	• Physical disintegration • Pyrolysis treatment • Dry etching • Precipitation
Recovery rate & purity	• >90% of glass • 95% of semiconductor materials (Si) • Up to 97% of intact wafers (>200 µm) • 6 N purity	• 90% of glass • 95% of semiconductor materials (Cd, Te) • >80% of Te of 99.7% purity	NA
Advantages	• High recovery rate of valuable materials • High purity of the recovered material • Possible direct reuse of wafers	• Capable of mixed waste treatment • High recovery rate of glass and semiconductor materials • Very automated process	• Capable of mixed waste treatment • High recovery rate of glass and semiconductor materials • Less use of chemicals • Less complicated process
Disadvantages	• Thin wafer defects and degradation due to high temperature • Inefficient manual separation • Potential harmful emissions	• Breakage of solar cells, not possible to reuse • Wafer reproduction required • High energy demand • Complicated process • Use of chemicals • Expensive equipment	• High energy demand • Breakage of solar cells, not possible to reuse • Wafer reproduction required • High effort required for purification

Commercial Examples of complete process in use for these solar panels:

Key Stages in the Recycling Process:

1. Module Separation

The solar panel is first disassembled into its main components:

- **Junction box:** Can be repaired and reused.
- **Cover glass:** Recycled as glass.
- **Back material:** Recycled into plastic.
- **Frame:** Typically aluminum, which is directly recovered for reuse.
- **Cells:** Further separated into:
  - **Crystalline silicon panels**
  - **Thin-film solar panels**

2. Recycling of Crystalline Silicon Panels

- **Heat Treatment:** Used to remove the encapsulants (like EVA) and separate silicon cells.
- **Chemical Processes:** Silicon cells undergo chemical treatments to recover pure silicon.
- **Recycling of Silicon:** The recovered silicon is purified for reuse in new solar panels or other industries.
- **Recycling Outputs:**
  - Silicon (Si): Reused in the electronics or solar industries.
  - Glass: Recycled and used in construction or manufacturing.

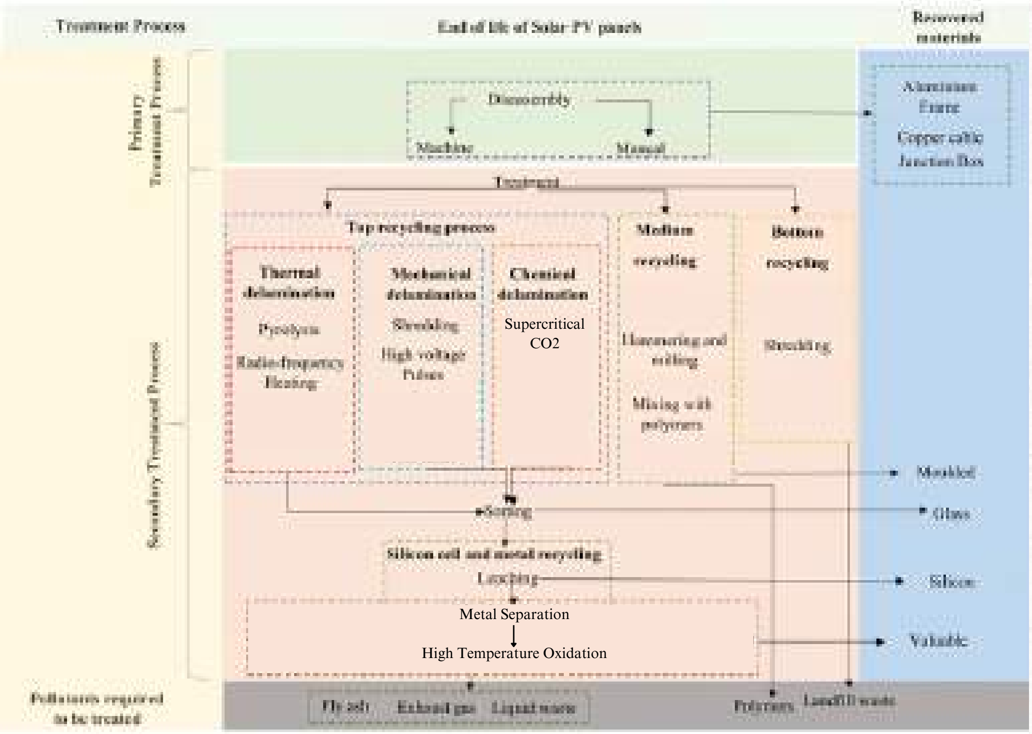
3. Recycling of Thin-Film Solar Panels

- **Processes to Recover Rare Metals:** These panels contain rare metals like indium, gallium, tellurium, and cadmium, which are recovered through various techniques:
  - **Grinding + Hydrometallurgy:** Dissolves metals like indium/gallium for recovery.
  - **Wet/Dry Mechanical Processing:** Extracts CdTe (cadmium telluride) or CIS (copper indium selenide).
  - **Physical + Chemical Methods:** Recovers tellurium and cadmium through combined approaches.
- **Outputs:** Rare metals are reused in high-tech applications.

4. Other Treatment Methods

- **Artificial Disassembly:** Manual separation of components when automated processes aren't feasible.
- **Acid/Alkali/Organic Solvent Dissolution:** Dissolves adhesive or binding materials to free the layers of the solar panel.
- **Ultrasound-Assisted Solvent Separation:** High-frequency waves are used to enhance material separation in an organic solvent environment.
- **Crushing + Electrostatic Separation:** Breaks down solar panels into smaller pieces and separates materials based on their electrical properties.

Detailed Recycling Process Overview



Primary Treatment Process: Disassembly of Solar Panels
(Extraction of Aluminium)

OBJECTIVE: To separate the main components of solar panels, such as the aluminum frame, copper cables, junction box, glass, and silicon cells, to make them ready for further recycling or reuse.

1. Machine-Based Disassembly - (for large scale)

The disassembly process can be automated to increase efficiency and reduce labor costs. Specialized machinery is used to detach various components with precision and speed.

Machines Used

- **Robotics Arms:** remove aluminum frames, junction box, and wiring
- **Automated Disassembly Lines:** separate aluminum frames and disconnect copper cables.
- **Robotic Cutters:** cut through the silicon cells and separate them from the glass.
- **Precision Screw Removers:** unscrew bolts and screws from the junction box and other parts.

2. Manual Disassembly - (for small scale)

Some components or areas of solar panels are difficult for machines to handle efficiently, requiring manual labor. Manual disassembly is often used to deal with such parts.

Machines Used

- **Screwdriver:** For manually removing screws from junction boxes or frames.
- **Wire Cutter:** To cut through any wiring that cannot be easily detached by machines.
- **Hand tools:** Workers may use pliers, hammers, or specialized tools to extract small parts or detangle wires.

End Products

Junction box
Valuable components sent for e-waste recycling.

Glass
Shredded for reuse in glass or solar panel production

Copper Cables
Recycled for purified copper use in industries.

Silicon Cells
Extracted for new solar cells or reuse in other lower efficiency required panels.

Aluminium Frame
Reused in solar panels or sent to metal recyclers.

Plastic Components
Shredded and sent for plastic recycling.

Aluminum Recycling: Processes, Machinery and End Products

1. Smelting - (for small scale)

Process Overview:

- **Collection & Separation:** Aluminum frames are manually separated and anodized aluminum is sorted.
- **Cleaning:** The aluminum is cleaned to remove impurities such as dirt, oils, and paint. This is done through mechanical or chemical cleaning methods.
- **Melting:** The cleaned aluminum is then melted in a furnace at a high temperature (around 660°C).
- **Purification**: During melting, impurities like silicon, iron, and copper are removed using Fluxing agents.
- **Casting:** Molten aluminum is poured into molds to form billets, ingots, or other shapes for reuse.

Machinery Required:

- **Shredders:** For breaking down large aluminum frames into smaller pieces.
- **Furnaces:** To melt the aluminum at high temperatures (typically induction or electric arc furnaces).
- **Crucibles**: To hold molten aluminum.
- **Casting Machines:** To form ingots or billets.
- **Fluxing Equipment:** For removing impurities.

End Products:

- **Aluminum Ingots/Billets:** These are the most common end products, used in various industries, including automotive, construction, and electronics.
- **Secondary Aluminum Products:** Recycled aluminum can be reused to create new products like frames for solar panels, cans and others.

2. Hot Excursion - (for large scale)

Process Overview:

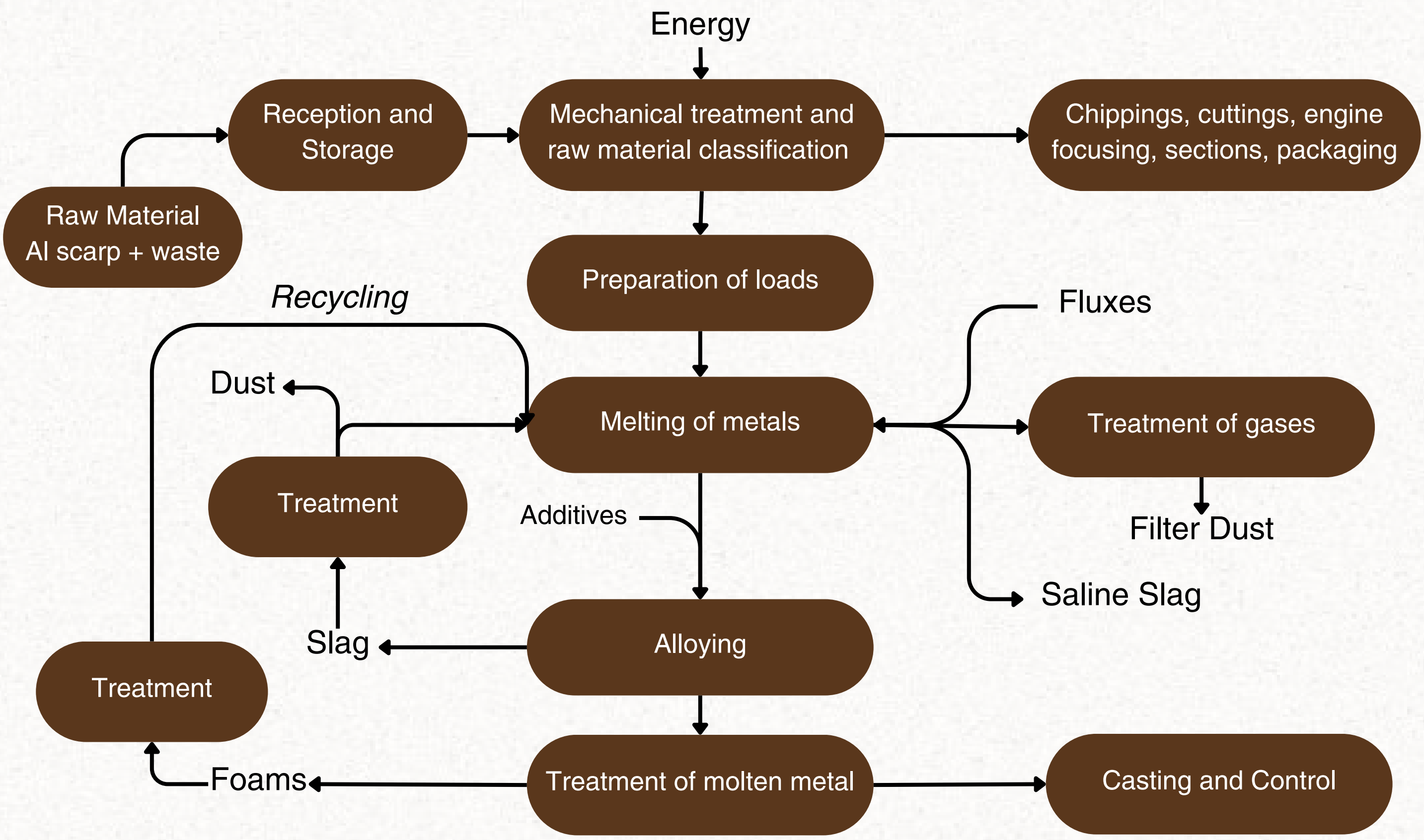
- **Preparation:** Aluminum scrap is shredded and cleaned to remove contaminants.
- **Electrolytic Process:** The scrap aluminum is submerged in a solution of sodium hydroxide ($NaOH$) or potassium hydroxide (KOH) and subjected to an electric current. The aluminum is dissolved, and pure aluminum is deposited onto the cathode.
- **Purification:** The electrolytic process ensures high purity by separating aluminum from other metals and impurities.
- **Collection & Casting**: The aluminum is collected from the cathode and cast into ingots or other reusable forms.

Machinery Required:

- **Electrolytic Cells:** Contain the electrolyte solution and anode/cathode for the electrolysis process.
- **Shredders:** For preparing aluminum scrap for the refining process.
- **Casting Equipment:** To form ingots after electrolytic refining.

End Products:

- **High-Purity Aluminum Ingots:** These are used in manufacturing high-end products, particularly where precise material properties are required (e.g., aerospace, electronics).



Secondary Treatment Process: Recycling and Recovery of Materials from Solar Panels (Extraction of Glass and Silicon)

OBJECTIVE: To recover valuable materials like silicon, glass, and metals from the broken-down solar panels, allowing for reuse in new solar panels or other manufacturing processes.

A. Top Recycling Approaches

i. Thermal Delamination

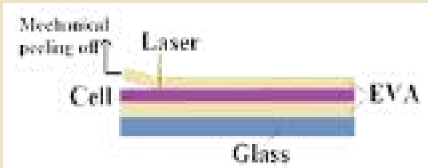
Thermal delamination involves applying heat to break the bonds between the materials, especially the polymers that hold the solar panel layers together. Different techniques of thermal treatment are used to separate the various components.

Pyrolysis (for small scale)

- Solar panels are heated in an oxygen-free environment, breaking down polymers and other adhesives without combustion.
- **Machinery:** Pyrolysis Reactors with temperature controls (operating at 400–600°C) for efficient decomposition of materials.
- **End Products:**
  - **Silicon wafers:** Recovered in a relatively pure form.
  - **Glass:** Cleaned and separated for recycling.
  - **Gaseous Byproducts:** These can be collected and used as fuel.
  - **Carbon Residue:** A byproduct that can be disposed of or used for other industrial applications.

Radio-Frequency Heating (for large scale)

- Electromagnetic waves are used to selectively heat adhesives and delaminate layers.
- **Machinery:** Radio-frequency Delaminators, which focus electromagnetic energy on the materials to heat them selectively.



- **End Products:**
  - **Cleaned Silicon:** Free from adhesives and other contaminants.
  - **Glass:** Also remains intact after delamination and can be easily recovered

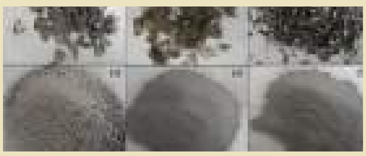
ii. Mechanical Delamination

Mechanical methods are used to physically break down the solar panels and separate their constituent materials, such as glass, silicon, and polymers.

Crushing (for small scale)

- **Process**: Solar panels are broken into smaller pieces, which are then sorted to separate the valuable components.
- **Machinery:** Industrial Shredders are used to shred panels into smaller fragments for further processing.
- **End Products:**
  - A mixture of shredded glass, silicon, and polymers, which requires further separation.

2-blade rotor crushing



Hammer crushing

High-Voltage Pulse Crushing HVPC (for large scale)

- **Process:** Electric pulses are applied to separate materials at their interfaces, particularly for breaking the bonds between the glass and silicon.
- **Machinery:** Electric Pulse Fragmentation Units generate high-voltage pulses to disassemble the materials.
- **End Products:**
  - **Glass fragments:** Recovered in clean form for reuse.
  - **Silicon fragments:** Also separated and cleaned for recycling.

Panel cut into small pieces

↓

Laminates placed in liquid dielectric

↓

High voltage pulses are applied to breakdown and discharge the laminates thereby crushing them

↓

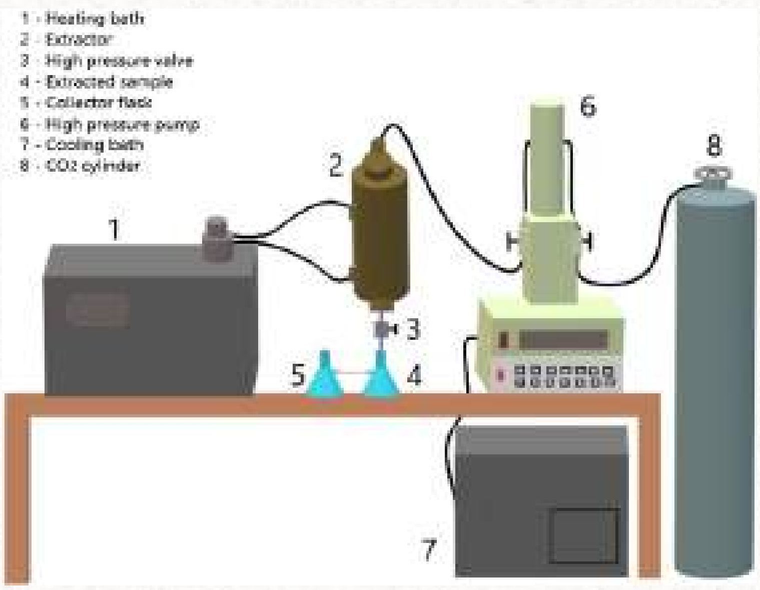
Mixed material is botained and seperated

iii. Chemical Delamination

Chemical methods use solvents to dissolve materials binding solar panel layers, effectively removing polymers, adhesives, and organics.

Supercritical CO2 (ScCO2) Delamination

- This method leverages the unique properties of supercritical CO2 to efficiently separate and recover materials from photovoltaic panels.
- **Machinery:** ScCO2 Chambers: These chambers operate under high pressure and temperature, enabling CO2 to achieve its supercritical state for optimal material separation.
- **Solvent Recovery System:** After the separation process, CO2 is recovered and recycled, reducing waste.
- **End Products:**
  - Recovered Silicon: The silicon is separated and can be purified for reuse in new solar panels or other electronics.
  - Valuable Metals: Metals like silver and aluminum are retrieved for reuse in manufacturing and electronics.



B. Medium Recycling Approaches

In the medium recycling approaches, mechanical and blending techniques are employed to further break down and process the materials extracted from solar panels. These methods are particularly useful for refining and preparing materials for reuse in secondary products.

i. Hammering and Milling

- This process involves using mechanical impact to break down the materials into smaller, more manageable particles. It is one of the primary methods for crushing and refining solar panel components like glass and silicon.

Process	The materials (e.g., glass, silicon, and metals) are subjected to high-impact forces that crush them into finer particles.	
Machinery	**Hammer Mills:** These are used to apply a mechanical force through hammers that impact and break the material down into smaller pieces.	**Ball Mills:** Another type of grinding equipment, ball mills use rotating cylindrical containers filled with grinding balls to crush the material.
End Products:	**Granulated Glass:** Shredded glass that has been crushed into finer particles, further processed for use in new manufacturing or construction materials.	**Silicon Granules:** Broken silicon particles that are smaller and easier to handle, ready for further refinement or incorporation into new products.
Applications	The granulated glass and silicon can be sent for further purification or used in the manufacturing of new panels or construction materials.	

ii. Mixing with Polymers

- After the materials from solar panels have been broken down, they can be blended with polymers to create composite materials. This approach allows for the creation of secondary products, which can be used in a variety of industries.

Process	Crushed solar panel materials are mixed with polymer resins to create new composite materials. This reduces both the recovered glass & silicon while also reducing waste.	
Machinery	**Polymer Mixing Units:** Machines that blend the crushed materials with liquid or powdered polymer resins, ensuring uniform distribution.	**Extrusion Systems:** Used to shape the mixed material into forms such as tiles, boards, or other molded products.
End Products:	**Composite Materials:** These can include items such as tiles, boards, or other molded materials that can be used in construction, flooring, or other industries. These products combine the recycled glass, silicon, and polymer resins into durable and usable goods.	
Applications	The composite materials produced from this process can be used in a variety of non-solar applications, such as in the construction of roofing tiles, flooring, or even in the manufacturing of plastic-based panels.	

C. Bottom Recycling Approach

The Bottom Recycling Approach is the final stage in the recycling process, focusing on the breakdown of solar panel components that cannot be efficiently recovered or reused. This approach primarily addresses waste minimization, turning non-recyclable materials into smaller components for safe disposal or landfill use.

i. Shredding

- Shredding is used to break down the solar panels into smaller, manageable pieces, particularly when materials are not viable for further recycling or reuse. It is often the initial step when dealing with materials that cannot be directly recycled or when the other recycling processes are not applicable.

Process	Solar panels are fed into industrial shredders that break down the panels into smaller fragments. This step reduces the size of the components, which makes it easier to segregate recyclable materials from waste materials.
Machinery	**Large-Scale Shredders:** These machines are designed to handle the volume and toughness of solar panel materials. They use rotating blades to crush the panels into smaller fragments, breaking apart glass, metal frames, silicon, and other elements.
End Products:	• **Mixed Waste Materials:** After shredding, the output is typically a mixture of materials, including: • Small pieces of glass, metal, and silicon. • **Non-recyclable materials** such as degraded polymers or adhesives. • **Portions Sent to Landfills:** Non-recyclable parts, such as contaminated polymers, adhesives, or any materials that cannot be processed further, are separated and sent to landfills for safe disposal.
Applications	• **Landfill Waste Minimization:** The shredding process helps in minimizing landfill space usage and preventing hazardous waste from being improperly discarded. • This bottom approach is essential when more advanced recycling techniques are not feasible for certain materials, ensuring that those components that cannot be reused or further processed are safely disposed of while minimizing environmental impact.

Silicon Cell and Metal Recycling

In the silicon cell and metal recycling process, valuable materials such as silicon and metals (e.g., silver, aluminum, copper) are recovered from the shredded components of solar panels. These materials are highly valuable in the production of new solar panels or in other industrial applications. The process is designed to maximize recovery while minimizing waste and environmental impact.

Goal: To extract valuable silicon and metals from the shredded solar panel materials, allowing for their reuse in new solar cells or in other industrial processes.

Steps Involved in Silicon Cell and Metal Recycling

Sorting → **Leaching** → **Metal Separation**

1. Sorting

Sorting is the first step in the silicon and metal recovery process, where the goal is to separate silicon and metals from the remaining shredded materials. This step helps in isolating the components that need further processing.

Process: After shredding, materials are sorted using optical and magnetic techniques to isolate silicon and metals.

Machinery:

- **Optical Sorters**: These machines use cameras and sensors to detect and separate materials based on their color, shape, or other optical properties. Optical sorters are particularly useful for separating silicon wafers from other materials.
- **Magnetic Separators:** These machines use magnetic fields to attract and separate ferrous metals (such as iron or steel) from non-metallic materials or other metals.

End Products:

- **Silicon:** Recovered silicon wafers or silicon-containing materials that can be purified and reused in new solar cells.
- **Metals:** Metals like copper, aluminum, and silver are isolated for further processing and recovery.

2. Leaching

Leaching is a chemical process used to extract valuable metals, such as silver and copper, from the materials collected during sorting. It involves dissolving metals using specific acids.

Process: The metals are dissolved into acidic solutions to separate them from the remaining material. This is typically used for recovering silver from the metallic contacts in solar cells or copper from wiring.

Machinery:

- **Leaching Tanks**: These are specialized containers where the shredded material is immersed in acidic solutions (such as sulfuric acid or nitric acid). The acid dissolves the metals, allowing them to be extracted.
- **Chemical Dosing Systems**: To control the amount and concentration of chemicals, dosing systems are used to ensure that the right conditions are maintained throughout the leaching process.

End Products:

- **Metal-Rich Solutions**: The output from leaching is a solution containing dissolved metals (such as silver, copper, and other trace metals) that can be further processed to recover the pure metals.

3. Metal Separation

Metal separation recovers and purifies metals like silver, copper, and aluminum from leached solutions using electrolysis and chemical precipitation. High-temperature oxidation removes organic residues and converts metals into oxides for further purification.

Process:

1. Electrolysis:
   - An electric current deposits dissolved metals onto electrodes for separation.
   - Commonly recovered metals include silver, copper, and aluminum.
2. Chemical Precipitation:
   - Precipitation agents are added to the leaching solution to form solid metal compounds.
   - These solids are filtered out to recover the metals.
3. High-Temperature Oxidation:
   - Organic residues (e.g., polymers and adhesives) are burned off, purifying silicon and converting metals to oxide forms like aluminum oxide and copper oxide.

Machinery:

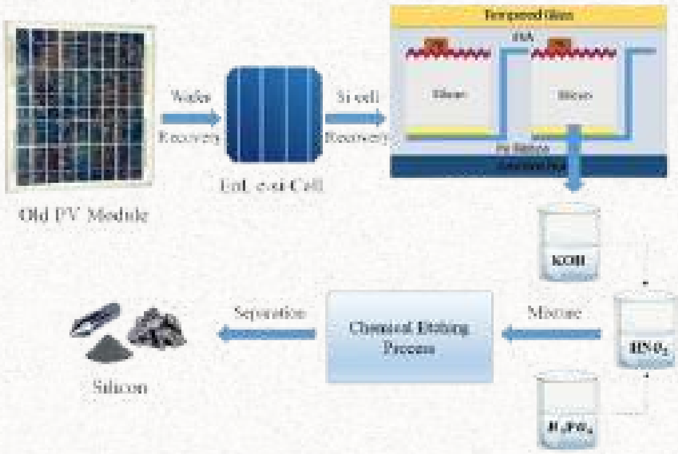
1. Electrolytic Cells:
   - Used for electrolysis, these cells apply an electric current to the leaching solution, depositing metals onto electrodes.
2. Precipitation Units:
   - Chemical reactors or tanks where agents are added to cause precipitation of metal salts, enabling separation.
3. Oxidation Furnaces:
   - High-temperature furnaces used to burn off organic residues, leaving purified silicon and metal oxides.

End Products: Pure Metals (Aluminium, Silicon, Copper) and Pure Silicon, reused in solar panel manufacturing.

Silicon Cell Recycling Process

1st generation Solar Panel
(Monocrystalline and Polycrystalline)

Crystalline silicon solar panels dominate 90% of the market due to high efficiency (15–22%) and durability. Widely used in rooftops and solar farms, they're ideal for residential, commercial, and utility-scale projects despite higher production costs compared to newer technologies.



2nd generation Solar Panel
Thin Film - Cadmium Telluride (CdTe), Amorphous Silicon (a-Si), Copper Indium Gallium Selenide (CIGS)

Thin-film solar panels (CdTe, CIGS, a-Si) are lightweight, flexible, and cost-effective, ideal for large-scale projects or unconventional surfaces. They hold about 10% of the market, with lower efficiency (10–13%) but better performance in low light and high temperatures, making them suitable for utility-scale or niche applications.

Crushed PV Waste
↓
Selenium reduced Precipitation using Hydrazine → Selenium
↓
Cementation using Indium → Copper
↓
Solvent Extraction D2EHPA membrane + Hydrochloric Acid → Gallium
↓
Electrolysis → Indium

for Copper Indium Gallium Selenide Panel (CIGS)

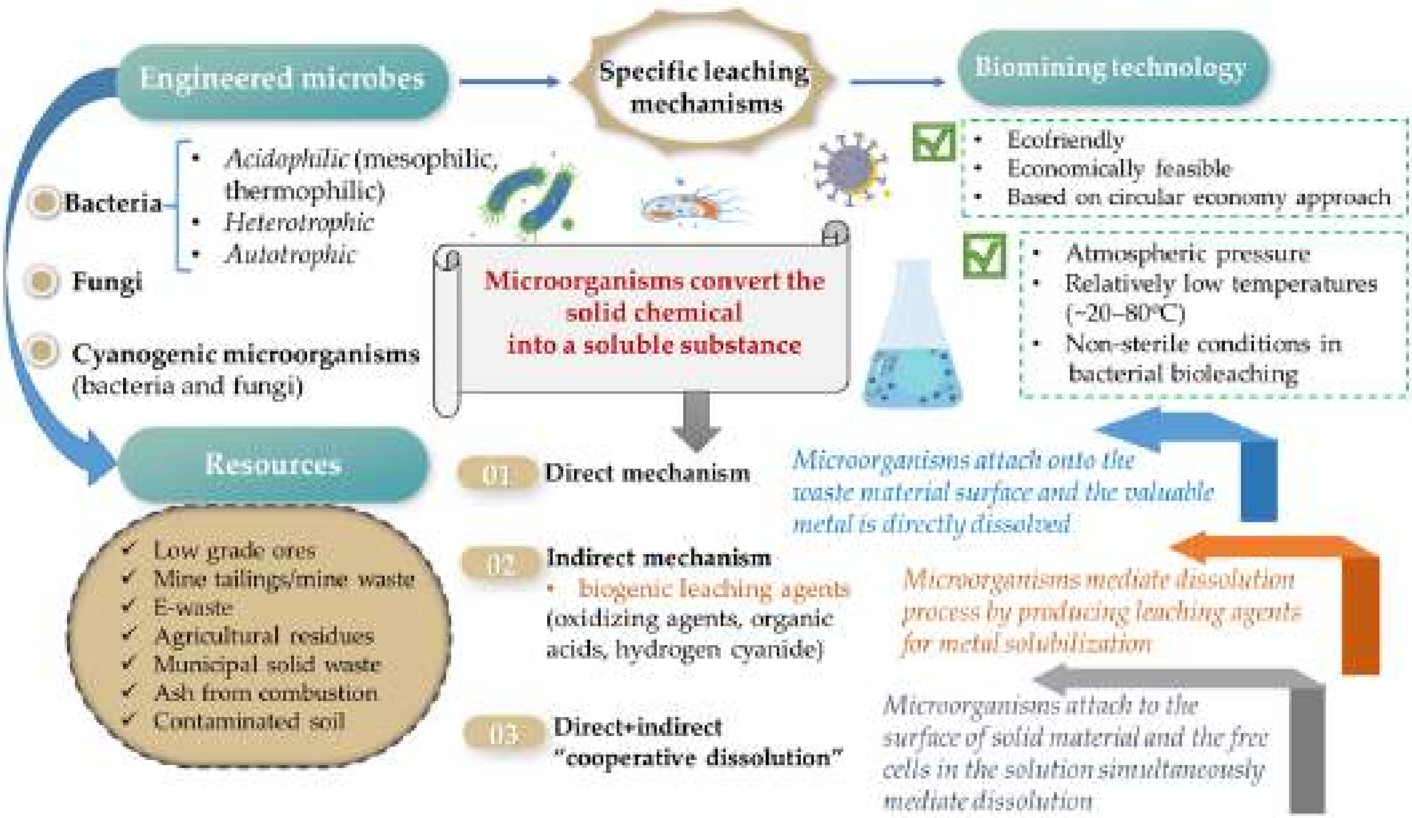
Crushed PV Waste
↓
Leaching Treatment $H_2SO_4 + H_2O_2$
↓
Cation Exchange Resin Amberlyst and Dowex
↓
Cadmium elution H_2SO_4 | Tellurium Metal
↓
Cadmium electrolysis | Evaporation
↓
Cadmium metal | $CdSO_4$

for Cadmium Telluride Panel (CdTe)

Technological Advancements

Bio-Recycling

Biorecycling encompasses **bioleaching** and **biooxidation**, which involve microbial mechanisms for solar panels recycling.
Bioleaching uses **autotrophic microorganisms** (iron- and sulfur-oxidizing) to solubilize base metals like copper, nickel, zinc, and cobalt.
Biooxidation employs microorganisms to remove mineral barriers around target metals, which are then solubilized in a secondary process, often for precious metals like gold and silver.



Schematic diagram of biomining process

Cyanogenic microorganisms (heterotrophic) produce hydrogen cyanide (HCN) to dissolve precious metals (e.g., gold), forming soluble complexes like [Au(CN2)]–

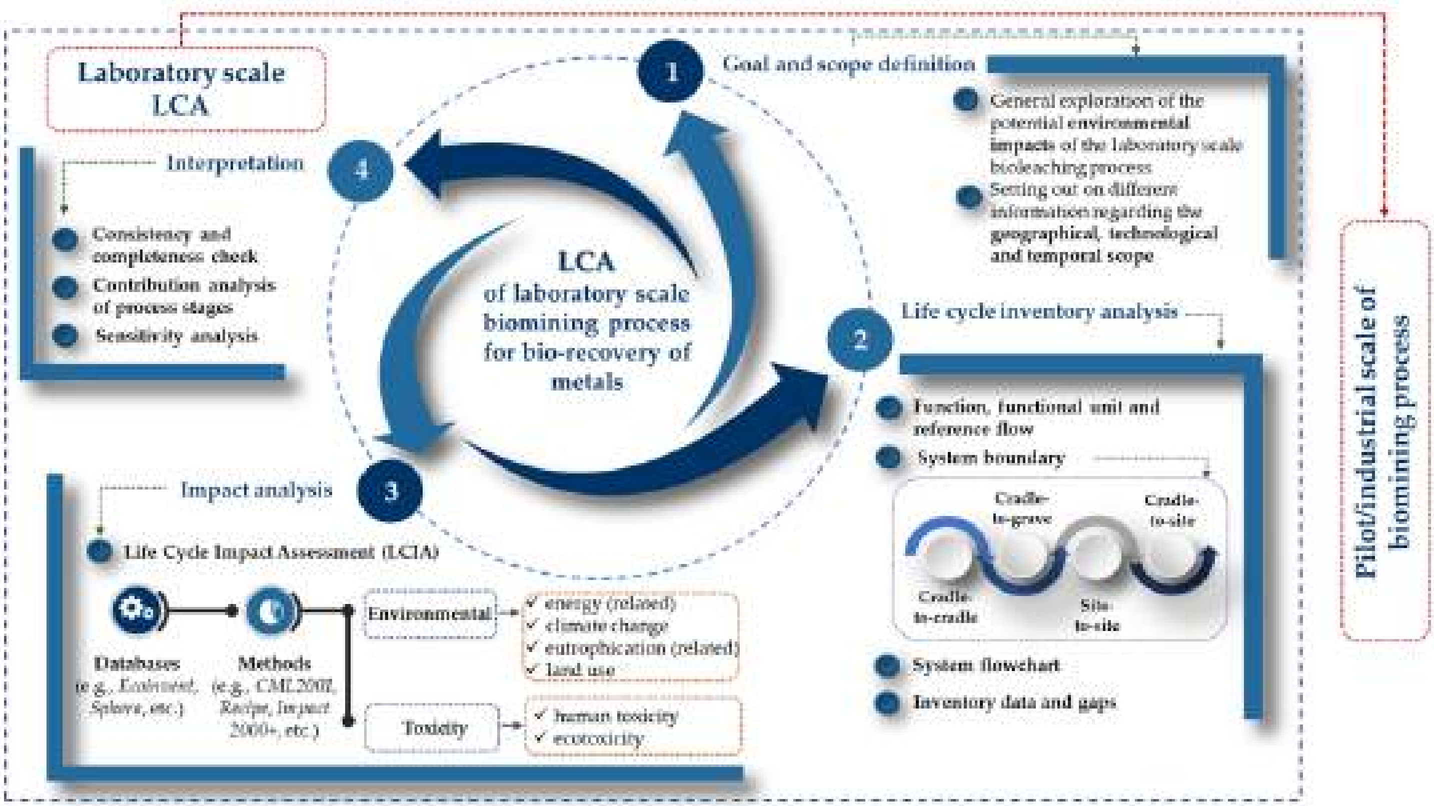
Optimal bioleaching conditions (pH = 2, 2% solids, 25°C, 20 days) achieved high metal recovery rates:

Zinc: 97%
Copper: 96%
Nickel: 93%
Lead: 84%
Cadmium: 67%
Chromium: 34%

Chemical leaching with FeCl3 was faster (48 h) but less efficient:

Zinc: 79%
Copper: 75%
Nickel: 73%
Lead: 70%
Cadmium: 65%
Chromium: 22%.

Copper bioleaching from **printed circuit boards (PCBs)** demonstrated **95–100% recovery within 48 hours** under specific conditions.



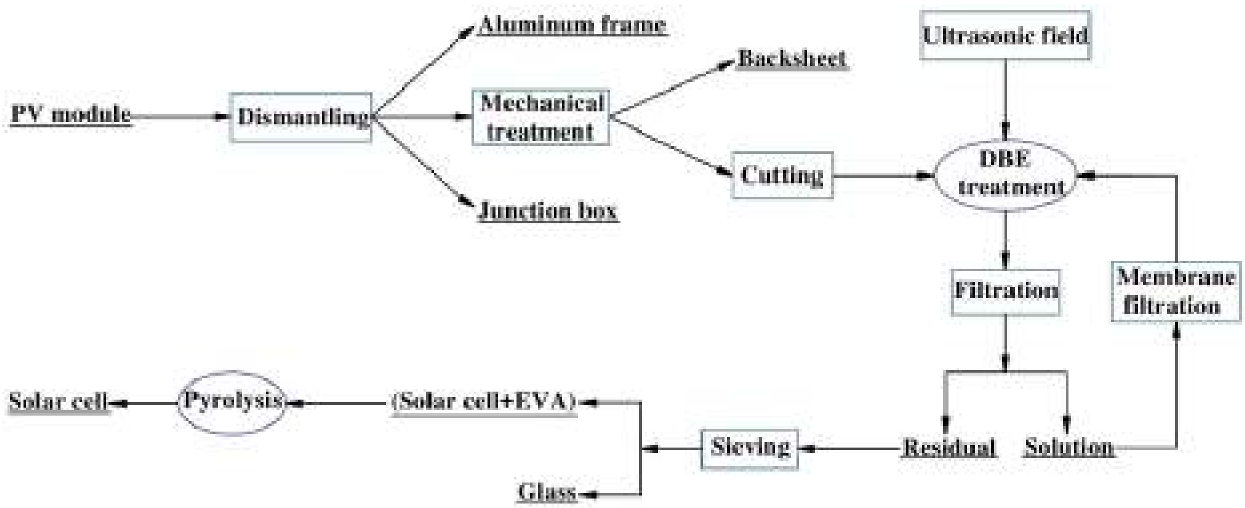
Upgrade of the biomining process for the bio-recovery of metals from laboratory scale to pilot/industrial scale using the four steps of LCA methodology.

Recycling of solar cells via swelling process

The premise of sufficiently recycling solar cells containing valuable resources from PV modules is to eliminate EVA for bonding glass, solar cells, and backsheet.
Compared with physical methods and pyrolysis, the **chemical swelling method for separating** different layers to recover solar cells has the advantages of **low energy consumption** and **high separation efficiency**.
However the toxicity of swelling reagents and the uncontrollable swelling process are major problems. Here in this context, a **novel green reagent dibasic ester (DBE, $C_{21}H_{36}O_{12}$)** was used to separate the glass EVA layer.
The **swelling of EVA by DBE is controllable**, which can prevent excessive cracking of solar cells.

Challenges in Recycling:

Effective recycling requires separating tightly bonded layers, including glass, solar cells and backsheet, connected by EVA (ethylene-vinyl acetate).
Existing physical and thermal methods have limitations, such as incomplete separation, excessive energy consumption, and environmental pollution.



Upgrade of the biomining process for the bio-recovery of metals from laboratory scale to pilot/industrial scale using the four steps of LCA methodology.

Novel Green Approach
Method using Dibasic Ester (DBE) for controlled swelling of EVA

Understanding Recycling Route:

- The route is energy efficient and reduces enviorenmental impact by avoiding flouride emissions from back sheets by pyrolysis
- Features an ideal boiling range (196–225°C) for controlled EVA swelling
- Ultrasonic power creates cavitation, accelerating DBE penetration into EVA
- Reusable DBE improves sustainability and reduces operational costs
- Offers a cleaner, more efficient alternative to conventional methods
- Glass separation pre-pyrolysis reduces energy use and improves resource recovery
- quality

Smart Bins

Smart bins are advanced waste management systems equipped with sensors, IoT technology, and sometimes AI, designed to optimize waste collection, sorting, and disposal.
They can detect waste levels, categorize materials, and track disposal patterns in real-time.
By automating processes like sorting and monitoring, smart bins improve **recycling efficiency**, **reduce contamination**, and **provide valuable data for waste management optimization**.

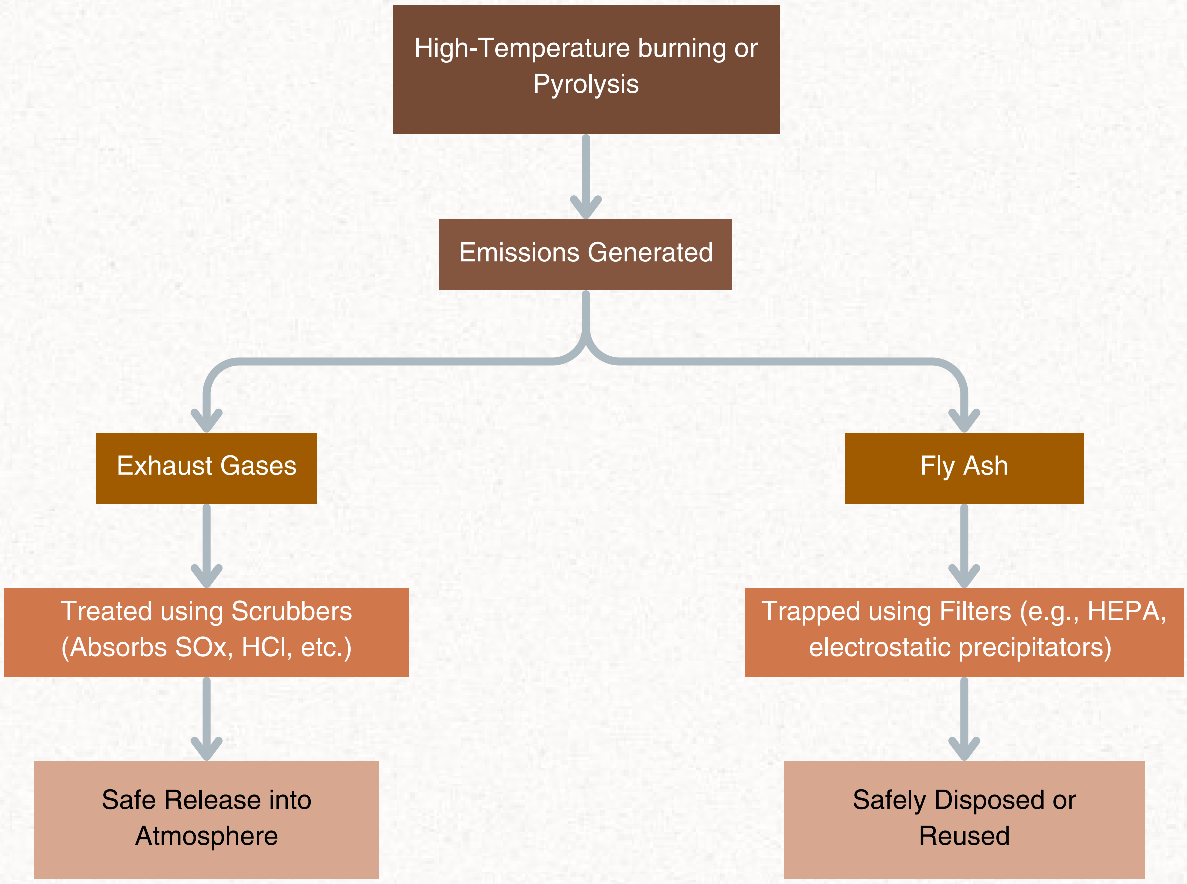
Material Sorting and Segregation	**Functionality:** Smart bins equipped with advanced sensors or AI algorithms can automatically identify and segregate materials. **Technology:** Optical sensors, RFID tags, and machine learning models employed to classify materials.
Condition Assessment	**Functionality:** Smart bins could assess the condition of the solar panels before they are sent for recycling. **Technology:** Pressure or strain gauges, or even visual inspection through cameras.
Tracking and Monitoring	**Functionality:** Smart bins can help track the volume, type, and source of solar panel waste ensuring that they are being disposed of in an environmentally responsible manner. **Technology:** IoT-enabled smart bins can be equipped with GPS and RFID systems to trace the origin and quantity of waste being disposed of. Data is sent in real-time to central monitoring systems.
Data Analytics for Optimisation	**Functionality:** By collecting data from multiple smart bins, the entire recycling process can be optimized over time. **Technology:** AI and machine learning algorithms can analyze the data to forecast future recycling needs, identify trends, and improve logistics.
Automation and Efficieny	**Functionality:** Smart bins can automate many tasks, from sorting materials to scheduling collections, reducing manual intervention. **Technology:** Bins could use robotics for automated sorting or engage with a central system that dynamically schedules pick-ups.
Energy and Environment Efficieny	**Functionality:** Ensures safe disposal of hazardous materials, such as cadmium telluride or lead. **Technology:** Sensors could monitor the air quality or detect hazardous chemical leaks from panels, triggering safety protocols.

Steps Involved in Pollution Control

To minimize the environmental impact of solar panel recycling by controlling airborne emissions (e.g., fly ash, exhaust gases) and treating liquid waste (e.g., leaching effluents) to ensure safe disposal and adherence to environmental standards.

1. Fly Ash & Exhaust Gas Management

During various recycling processes, especially when dealing with high-temperature treatments like pyrolysis or burning, harmful emissions such as fly ash and exhaust gases may be produced. These pollutants need to be captured and neutralized to prevent air contamination.



2. Liquid Waste Treatment

The recycling process, especially during chemical leaching (used to extract metals from shredded panels), can generate Leachate or other wastewater produced during metal recovery and chemical processing that contain harmful substances such as heavy metals, acids, and other chemicals. These effluents need to be treated to neutralize harmful chemicals and remove any hazardous materials before they are released into the environment.

- **Machinery:**
  - **Wastewater Treatment Plants:** These facilities are equipped with various treatment processes, including chemical neutralization, filtration, and precipitation, to remove heavy metals and other contaminants from the liquid waste.
  - **Chemical Dosing Systems:** In some cases, chemicals like lime or sodium hydroxide are added to adjust the pH of the effluent, neutralizing acids or precipitating metals for easier removal.
  - **Sedimentation Tanks:** Used to allow heavier particles like metals or other solids to settle at the bottom for collection.
- **End Products:**
  - **Treated Water:** After treatment, the water can be safely discharged into the environment or reused in the recycling process.
  - **Solid Waste:** Sludge containing precipitated metals or other contaminants that need to be disposed of in an environmentally responsible manner, possibly by sending it to a hazardous waste facility.

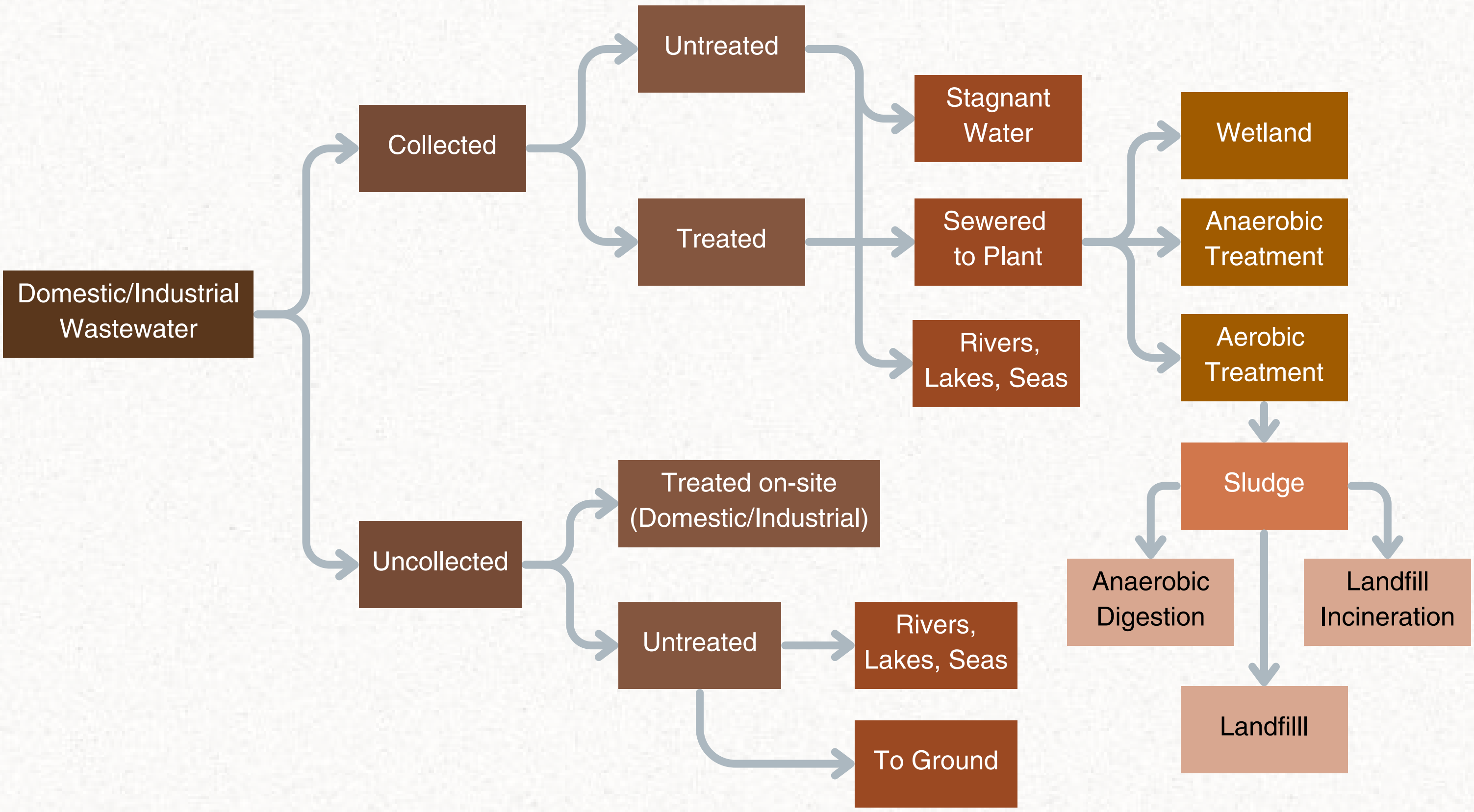
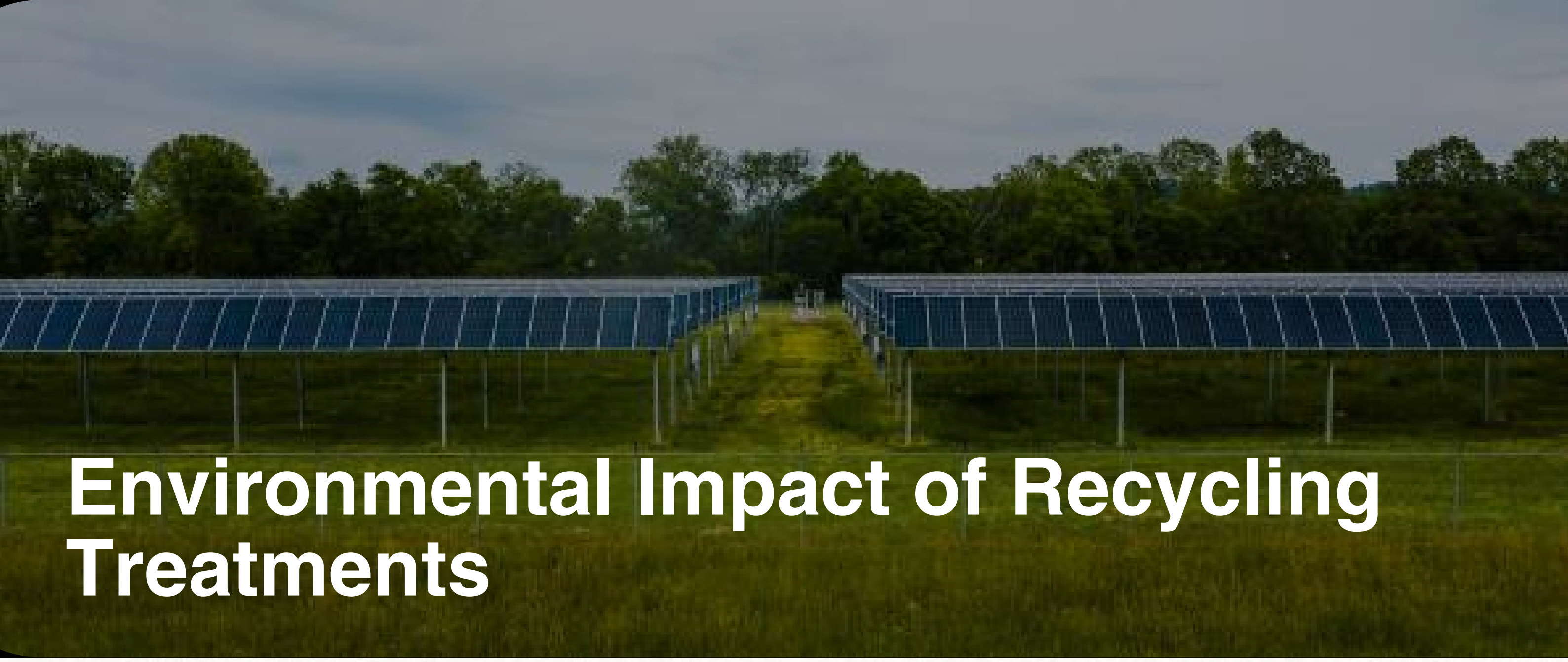


Diagram: Liquid Waste Treatment Process flowchart illustrating the liquid waste treatment process, from generation to safe disposal



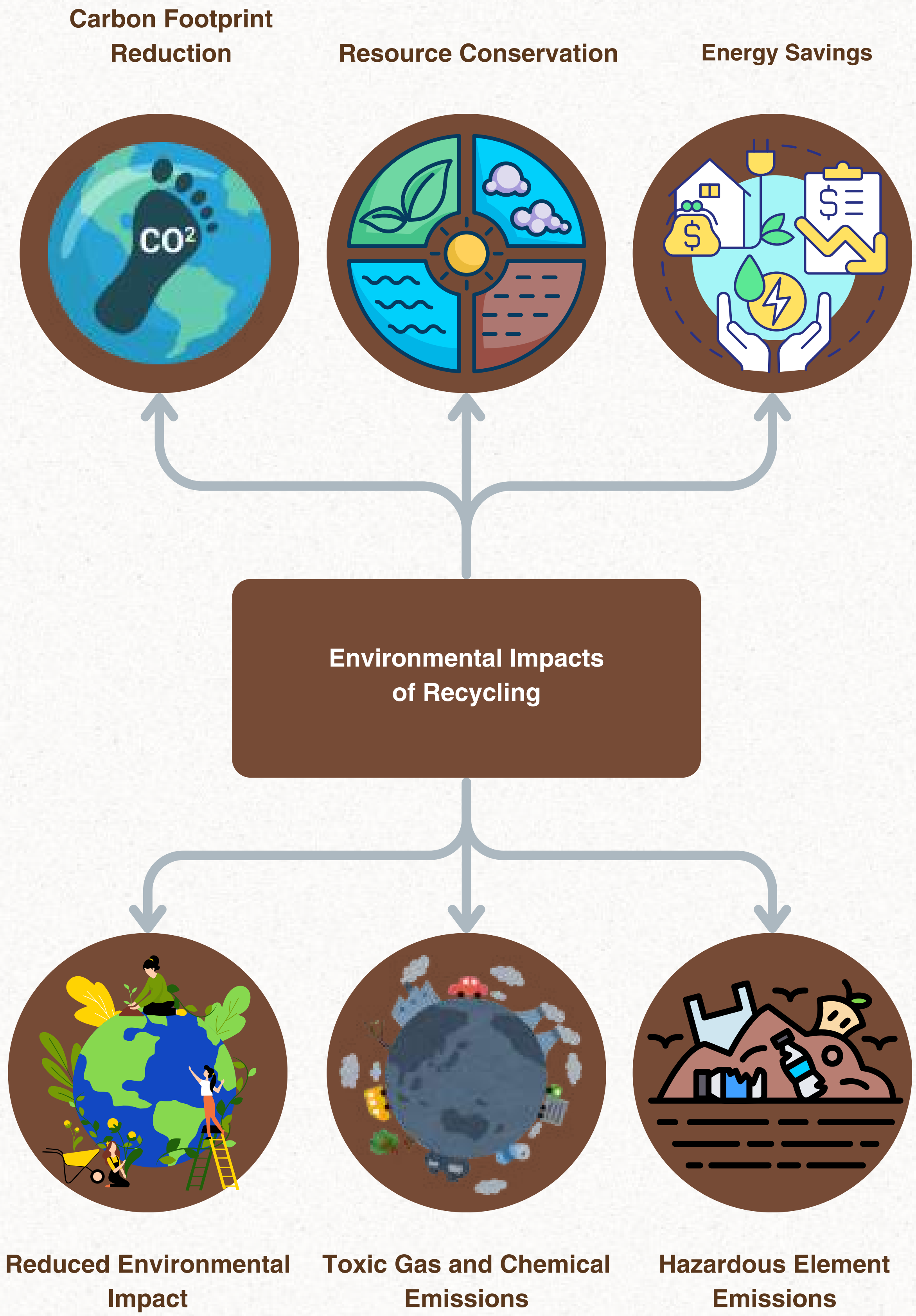
Environmental Impact of Recycling Treatments

Advantages

- **Carbon Footprint Reduction:**
  - Recycling PV waste significantly reduces environmental impacts by lowering CO_2 emissions by **1.1 E+11 kg**, saving **1.1 E+12 kg** of industrial water, and generating **3.6 E+11 MJ** of energy. It also offers an estimated net economic benefit of **$13 billion**. Manufacturing using recycled silicon emits less CO_2 compared to traditional silicon carbide production.
- **Resource Conservation:**
  - Recycling prevents hazardous metals like lead, cadmium, and rare elements from leaching into the environment. It preserves natural and rare metals while **protecting water sources** from contamination.
- **Energy Savings:**
  - Producing silicon wafers from recycled materials requires significantly **less energy** than producing them from raw materials. This helps reduce the overall energy footprint of the PV manufacturing process.
- **Reduced Environmental Impact:**
  - Reclaimed materials like glass, silicon, and metals **reduce environmental impact** across multiple categories, including raw material extraction, waste management, and resource depletion.

Disadvantages

- **Toxic Gas and Chemical Emissions:**
  - The pyrolysis process for recycling PV panels generates harmful emissions. For example, processing 0.589 kg of crushed PV panels produces 0.133 kg of gases (including CO_2, CO, H_2, and halogens such as bromine and chlorine) and results in indirect emissions of approximately 1.7 kg CO_2 equivalent per kg of silicon recovered.
- **Hazardous Element Emissions:**
  - Pyrolysis releases hazardous substances such as lead and cadmium in flue gases, necessitating advanced filtration systems like electrostatic precipitators or fabric filters. Chemical treatments, such as using nitric acid and solvents, generate toxic by-products, including nitrogen oxides, fluorides, and silicon species, which pose significant disposal and environmental challenges.


Carbon Footprint Reduction
Resource Conservation
Energy Savings
CO2
Environmental Impacts of Recycling
Reduced Environmental Impact
Toxic Gas and Chemical Emissions
Hazardous Element Emissions

Policies and Framework

Solar energy is a cornerstone of India's renewable energy strategy, with ambitious targets such as achieving **270 GW** of solar capacity by **2030** under the National Solar Mission. However, as solar panel installations grow, so does the challenge of managing end-of-life solar waste, projected to reach **268358 kilotons by 2030** and **16682000 kilotons by 2050**. Addressing this pressing issue requires robust policies, frameworks, and innovative solutions to ensure sustainable solar waste management.

This section outlines the existing regulations and standards governing solar waste management in India and globally, highlights the gaps in the current systems, and proposes advanced measures tailored to India's unique socio-economic and environmental landscape. These insights aim to pave the way for a circular economy in the solar industry, ensuring resource efficiency and environmental sustainability.

Existing Policies

In India, solar waste management is currently governed by the **Electronic Waste Management Rules 2022**, which mandates that manufacturers and producers of solar photovoltaic modules, panels, and cells are responsible for storing their generated waste until **2034-2035**, following guidelines set by the **Central Pollution Control Board (CPCB)**; essentially placing solar waste under the umbrella of e-waste management, requiring them to collect, store, and arrange for recycling of their solar waste products.

The Ministry of Environment, Forest, and Climate Change notified the **E-Waste (Management) Rules, 2022**, on November 2, 2022, incorporating the management of solar photovoltaic (PV) modules, panels, and cells under **Chapter V** on March 14, 2023.

As per these rules, manufacturers and producers must:

- Register on the designated portal.
- Store solar PV waste generated until 2034-35 per Central Pollution Control Board (CPCB) guidelines.
- File annual returns on the portal by the end of each applicable year, up to 2034-35.
- Process non-solar PV waste according to existing rules and guidelines.
- Maintain a distinct inventory of solar PV waste on the portal.
- Adhere to standard operating procedures issued by CPCB.

Challenges in Solar Waste Policy Framework in India

Ambiguity in Guidelines and Regulations

Unclear guidelines for managing solar PV waste result in inconsistent implementation and poor compliance.

No Penalty or Landfill Tax

Without penalties or landfill taxes, there is little incentive to properly recycle solar waste instead of disposing of it improperly.

Absence of a National Monitoring and Reporting (M&R) System

The lack of a centralized system for tracking solar PV waste prevents effective monitoring of generation, recycling, and reuse activities.

Inadequate Information Dissemination

Poor communication about recycling rates, EPR guidelines, new technologies, and job opportunities reduces stakeholder participation.

Lack of a Financial Regulatory Body

The absence of a dedicated body to oversee financial aspects of PV waste management deters investments in recycling infrastructure.

Global Landscape

European Union (EU) WEEE Directive on PV Module Waste Management Directive

- **Waste Electrical and Electronic Equipment (WEEE) Directive** (Directive 2012/19/EU)
- **Adoption Year:** 2012 (revised to include PV modules)
- **Primary Objective:** Establish a framework for the collection, recycling, and responsible disposal of electrical and electronic waste, including photovoltaic (PV) modules.

Key Provisions

- **Producer Responsibility:**
  - Producers are responsible for financing the collection, treatment, recovery, and recycling of PV waste.
  - They must register with national authorities and provide regular reports on the quantity of PV modules placed on the market and collected as waste

.

- **Marking and Labeling:**
  - All PV products must be labeled with a crossed-out wheel-bin symbol to indicate they should not be disposed of with regular waste.

- **Collection Targets:**
  - Member states must ensure that a minimum percentage of PV waste is collected annually, based on the average weight of PV products placed on the market over the previous three years.

- **Recycling and Recovery Targets:**
  - PV modules must meet specific recovery rates:
    - 85% of the material must be recovered.
    - 80% of the material must be prepared for reuse or recycling.

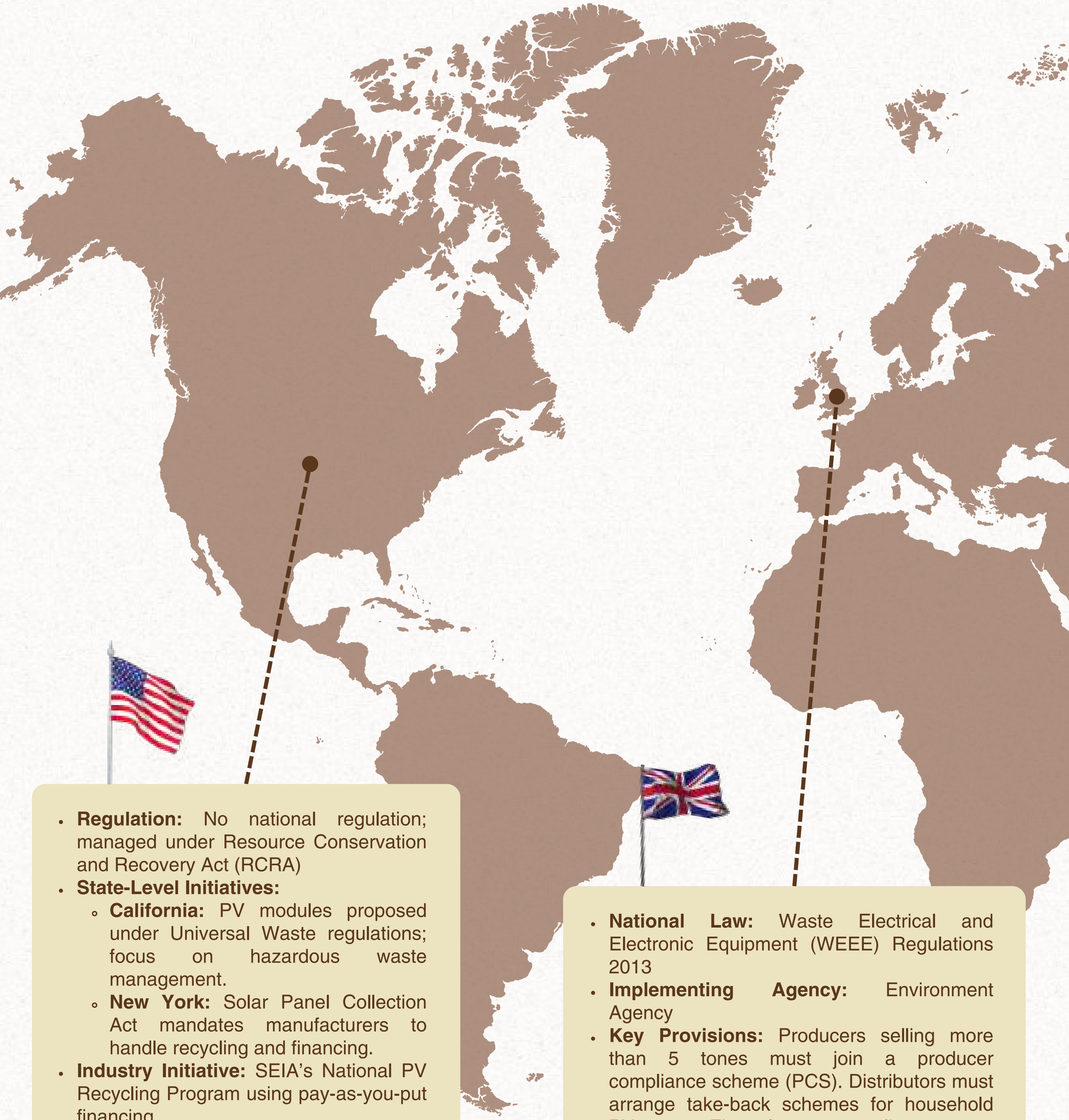
- **Reporting and Compliance:**
  - Producers must submit annual reports detailing the amount of PV waste collected, treated, and recycled.
  - Non-compliance can result in significant financial penalties or a halt in sales activities.

Impact and Global Leadership

- The EU is recognized as a global leader in PV waste management, with a comprehensive framework for recycling and recovery.
- The WEEE directive has set a benchmark for other regions, promoting sustainable practices and circular economy principles in the solar industry.

The EU's WEEE Directive has revolutionized PV waste management by enforcing producer accountability and stringent recycling standards. This proactive approach ensures long-term sustainability and inspires global adoption of similar frameworks.

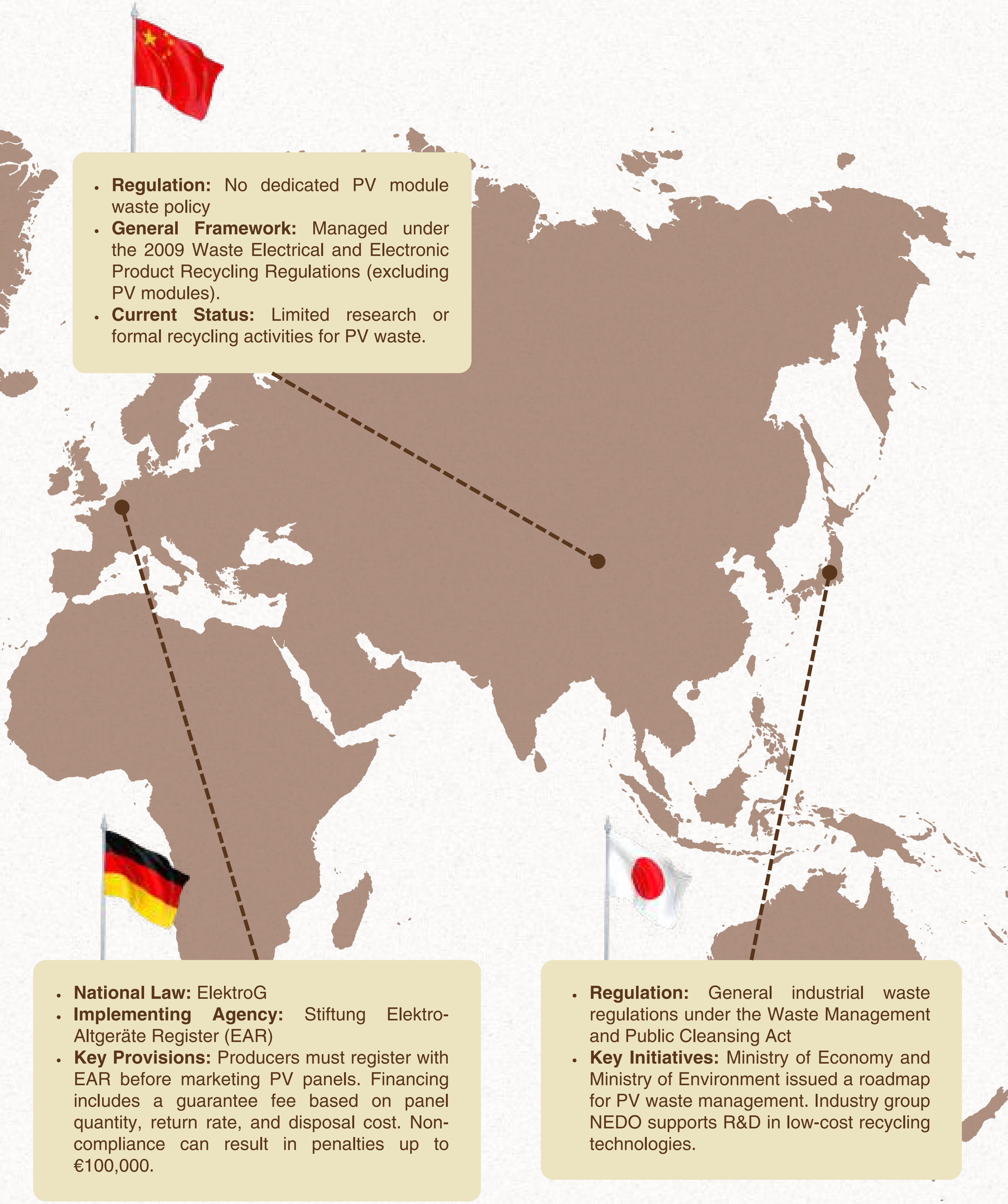
Global Scenarios



- **Regulation:** No national regulation; managed under Resource Conservation and Recovery Act (RCRA)
- **State-Level Initiatives:**
  - **California:** PV modules proposed under Universal Waste regulations; focus on hazardous waste management.
  - **New York:** Solar Panel Collection Act mandates manufacturers to handle recycling and financing.
- **Industry Initiative:** SEIA's National PV Recycling Program using pay-as-you-put financing.

- **National Law:** Waste Electrical and Electronic Equipment (WEEE) Regulations 2013
- **Implementing Agency:** Environment Agency
- **Key Provisions:** Producers selling more than 5 tones must join a producer compliance scheme (PCS). Distributors must arrange take-back schemes for household PV waste. Fines for non-compliance range from £5,000 to unlimited fines.

Global Scenarios



- **Regulation:** No dedicated PV module waste policy
- **General Framework:** Managed under the 2009 Waste Electrical and Electronic Product Recycling Regulations (excluding PV modules).
- **Current Status:** Limited research or formal recycling activities for PV waste.

- **National Law:** ElektroG
- **Implementing Agency:** Stiftung Elektro-Altgeräte Register (EAR)
- **Key Provisions:** Producers must register with EAR before marketing PV panels. Financing includes a guarantee fee based on panel quantity, return rate, and disposal cost. Non-compliance can result in penalties up to €100,000.

- **Regulation:** General industrial waste regulations under the Waste Management and Public Cleansing Act
- **Key Initiatives:** Ministry of Economy and Ministry of Environment issued a roadmap for PV waste management. Industry group NEDO supports R&D in low-cost recycling technologies.

Policy Recommendation

Solar Sustainability Certificates

The government should introduce **Solar Sustainability Certificates(SSC).** These certificates will be awarded to producers and manufacturers who meet annual recycling targets. Incentivizing recycling, enhancing brand reputation, and driving compliance with EPR policies.

Landfill Penalty

The government should impose a **Landfill Penalty** on manufacturers who dispose of end-of-life (EOL) or damaged solar panels in landfills instead of recycling them. This penalty system aims to deter improper disposal practices and ensure responsible waste management across the solar industry.

Green Job Creation Policy

The government should implement a **Green Job Creation Policy**. This policy will focus on skill development, formalizing the informal waste sector, and fostering partnerships with NGOs and research institutions to create a robust, skilled workforce for recycling operations.

Promoting Public Responsibility Organizations(PRO)

Government support to **Public Responsibility Organizations (PROs)**. These third-party, private organizations will manage the collection and recycling of end-of-life (EOL) solar panels, ensuring sustainable waste management.

Benefits of Policies

Solar Sustainability Certificate (SSC)

1. **Financial Incentives:**
    - Certified manufacturers can receive tax credits or subsidies, lowering operational costs and boosting profitability.
2. **Brand Recognition and Marketing Advantage:**
    - The certificate acts as a mark of sustainability, enhancing brand reputation and attracting eco-conscious consumers and investors.
3. **International Trade and Technology Access:**
    - Certified companies gain preferential access to advanced recycling technologies and trade benefits, supporting easier import of sustainable innovations and boosting global market credibility.

Green Job Creation Policy

1. **Job Creation and Economic Boost:**
    - Creates employment in rural and semi-urban areas, building a skilled green economy workforce and supporting local economic growth.
2. **Reduced Transportation and Labor Costs:**
    - Local recycling hubs and trained workers minimize transportation distance, cutting costs and ensuring fair wages while eliminating unsafe labor practices.
3. **Efficient Waste Management:**
    - Promotes proper collection, handling, and recycling of solar panel waste, reducing environmental risks and enhancing the recycling ecosystem's efficiency and scalability.

Landfill Penalty

1. **Environmental Protection:**
    - Prevents toxins like cadmium and lead from contaminating soil and water, reduces landfill waste, and supports a cleaner ecosystem through sustainable waste management.
2. **Increased Motivation for Recycling:**
    - Financial penalties incentivize manufacturers to prioritize EOL and damaged panel recycling and drive investment in recycling infrastructure and innovative technologies.
3. **Enhanced EPR Compliance:**
    - Ensures accountability through lifecycle tracking and transparent reporting, promoting a circular economy by encouraging material reclamation and reducing raw resource extraction.
    - .

Promoting Public Responsibility Organizations(PRO)

1. **Reduced Burden on Manufacturers:**
    - Manufacturers can concentrate on production without managing recycling infrastructure or specialized staff, cutting operational costs related to recycling.
2. **Boost to Employment:**
    - PROs generate jobs in formal and informal sectors, offering opportunities for both skilled and unskilled workers, while ensuring fair wages and better working conditions, formalizing the informal waste sector.
3. **Economic Growth and GDP Boost:**
    - Enhanced recycling efficiency and job creation stimulate economic activity and GDP. Public-Private Partnerships (PPPs) foster innovation, infrastructure development, and industrial growth, reinforcing economic resilience.

Implementation Strategy

0-1 year

- Develop and launch the framework for Solar Sustainability Certificates.
- Establish eligibility criteria, recycling targets, and a verification process for awarding certificates.
- Announce tax credits and subsidies tied to these certificates.
- Implement mandatory annual reporting by manufacturers on sold, collected, and recycled solar panels.
- Set up monitoring systems for landfill disposal and establish penalty thresholds.
- Introduce penalty enforcement mechanisms and publish compliance guidelines.

1-2 years

- Partner with NGOs, technical institutes, and research organizations to create recycling training programs.
- Launch pilot recycling units in selected rural or semi-urban areas.
- Introduce a certification program for informal sector workers joining the formal recycling system.
- Establish legal and operational frameworks for PRO formation and registration.
- Offer government support through transportation subsidies and tax incentives for recycling units.
- Promote private investment and public-private partnerships with industry workshops and forums.

3-4 years

- Expand the scope of the certificates to include additional sustainability metrics like energy efficiency and carbon footprint reduction.
- Promote international recognition for these certificates, enhancing trade benefits and technology collaborations.
- Integrate certificates into branding and marketing campaigns, making them industry standards.
- Establish **real-time tracking systems** using digital technologies like IoT and AI to monitor the disposal and recycling of solar panels.
- Implement **progressive penalties** with increasing fines for repeated non-compliance.
- Develop **public awareness campaigns** to ensure all stakeholders understand the importance of compliance.

4-6 years

- Scale up national-level skill development programs, integrating modern recycling technologies and sustainable waste management practices.
- Establish regional recycling hubs in all major solar panel deployment zones to decentralize waste management.
- Formalize informal sectors with employment benefits, ensuring job security and fair wages.
- Expand PRO operations nationwide, ensuring **coverage across rural and urban regions**.
- Provide **grants and low-interest loans** for PROs to adopt advanced recycling technologies.
- Promote **profit-sharing models** between PROs and manufacturers to foster long-term partnerships and economic sustainability.

Circular Economy

Proposed Model for Circular Economy

The proposed circular economy model for solar panel waste management integrates sustainability and efficiency by ensuring that all stakeholders contribute to a closed-loop system. **Producers** manufacture solar panels, which are adopted by **consumers** with **government**-subsidized incentives to promote green energy. At the end of their lifecycle, solar panel waste is managed by **Public Responsibility Organizations (PROs)**, supported by the government through resources like transportation, tax benefits, and advanced machinery. The PRO collects and recycles the waste, supplying reprocessed raw materials back to producers or other industries and refurbishing panels for low-energy usage areas. This collaborative system ensures resource optimization, waste reduction, and equitable energy access.

Roles of Stakeholders

Producers

- Manufacture solar panels and supply them to consumers.
- Collaborate with Public Responsibility Organizations (PROs) for waste collection, recycling, and reusing raw materials.
- Face penalties from the government for not achieving recycling targets.

Government

- Offers subsidies to consumers, encouraging the adoption of solar panels and green energy solutions.
- Supports PROs by providing resources like transportation, tax incentives, advanced technologies, and machinery for recycling.
- Monitors producer compliance and enforces penalties for lapses.

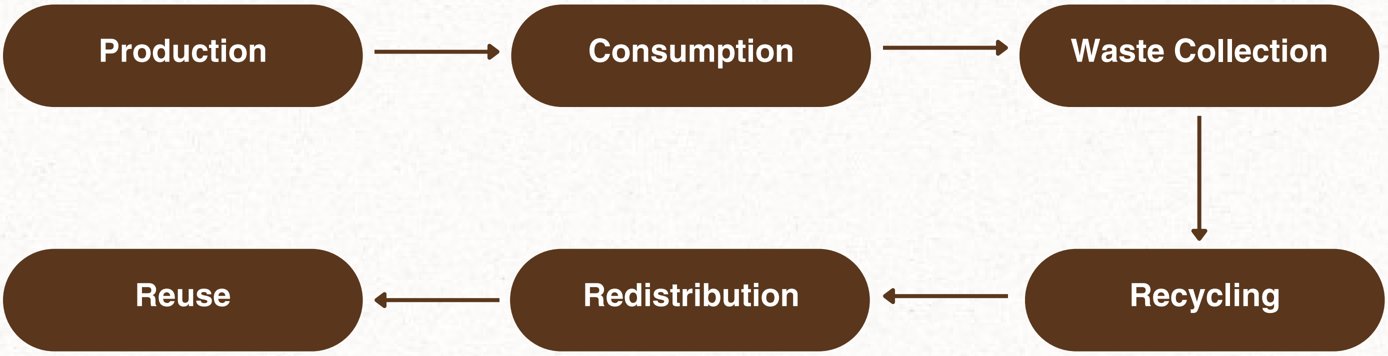
PROs

- Collects solar panel waste from consumers, with active involvement from the informal sector and government-backed support.
- Manages transportation of waste to recycling facilities.
- Processes waste to extract raw materials or refurbish panels with reduced efficiency for use in low-energy demand areas like rural and semi-urban regions.
- Sells recycled raw materials to producers or related industries, ensuring profitability.

Consumers

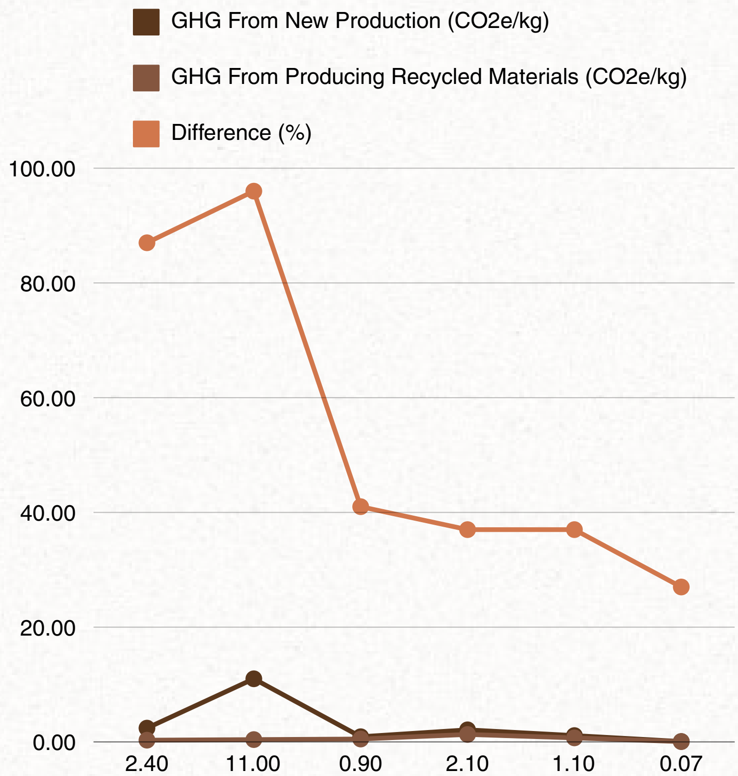
- Use solar panels for energy consumption.
- Ensure that solar panel waste is handed over to PROs at the end of its lifecycle or in case of pre-mature disposal.

Lifecycle Flowchart



Circular Economy Flow

- **Manufacturing:** Producers create solar panels using either virgin or recycled raw materials.
- **Consumption:** Solar panels are used by consumers with government-subsidized incentives.
- **End-of-Life Management:**
    - PRO collects solar panel waste and sends it to recycling facilities.
    - Refurbished panels are redistributed for low-energy requirements.
    - Recycled raw materials are reintegrated into the supply chain for producers and other industries.
- **Feedback Loop:** Continuous collaboration between PRO and producers ensures materials are sustainably reused, minimizing waste.



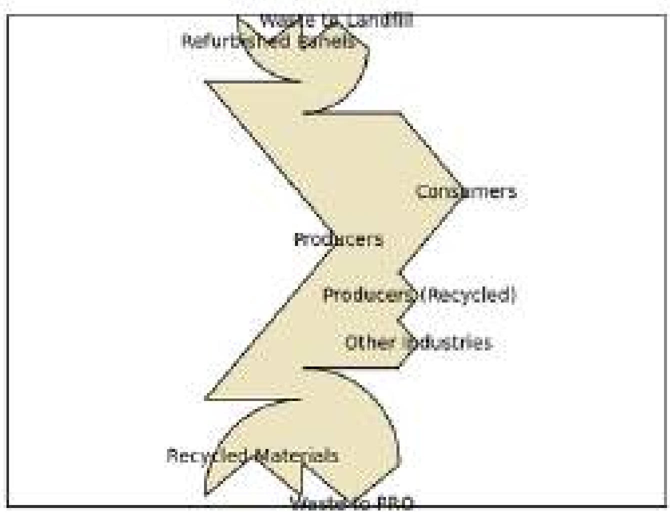
Sustainability Goals

This model achieves:

- **Resource Efficiency:** Recycling reduces reliance on virgin materials.
- **Waste Reduction:** Proper disposal prevents environmental harm.
- **Economic Gains:** Raw materials are sold at reduced prices, benefiting industries while maintaining PRO profitability.
- **Energy Equity:** Refurbished panels power underserved regions, promoting inclusivity.

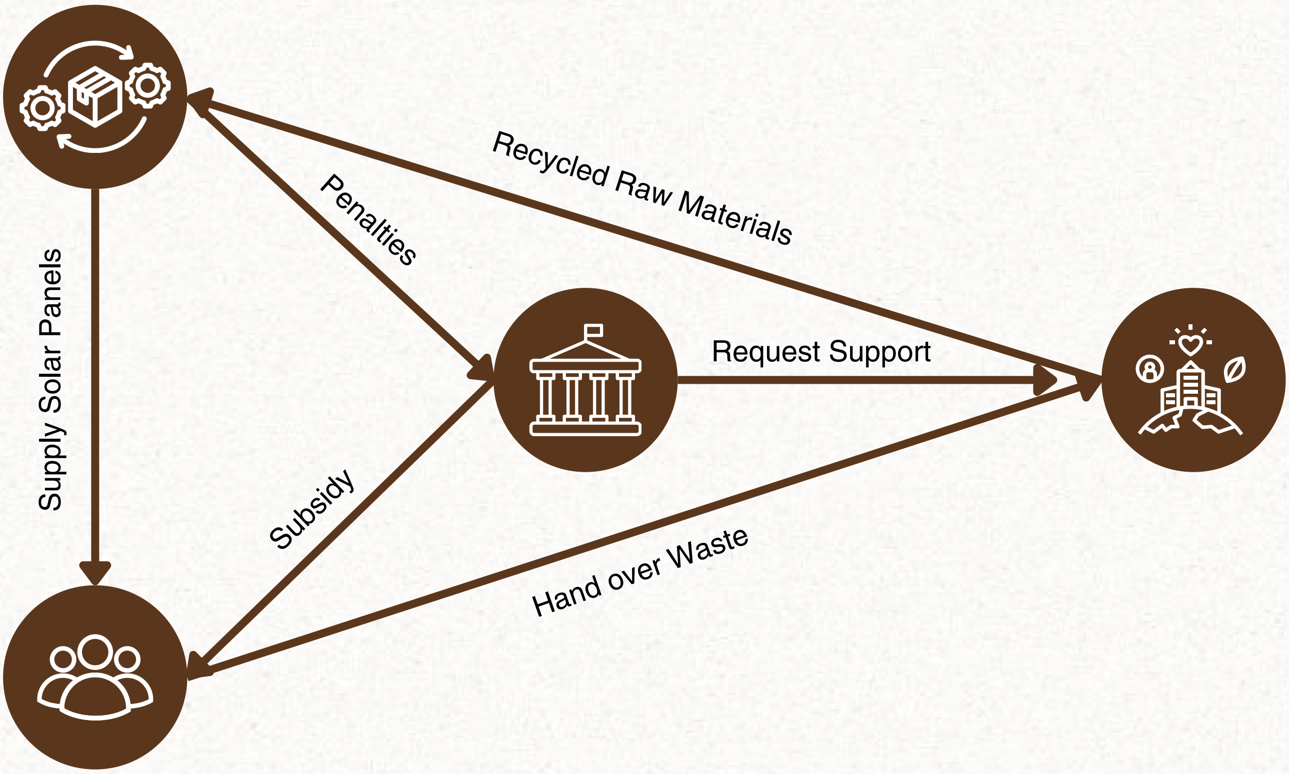
Sankey Diagram:

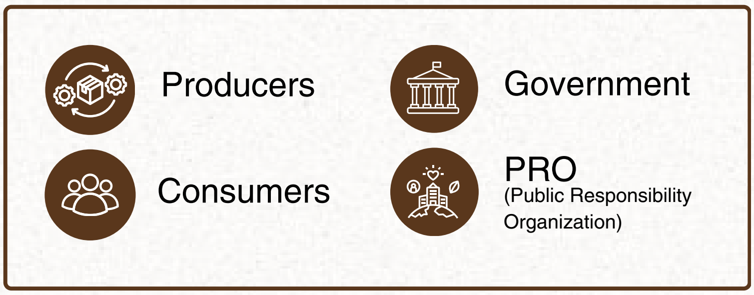
Material and Waste Flow in Circular Economy Model



The Sankey diagram illustrates the material flow in the solar panel recycling ecosystem, starting from consumers and producers to recycling processes. It shows how waste panels are refurbished or recycled into materials for other industries, reducing landfill waste and promoting circularity.

Interactions Among Stakeholders in Solar Panel Waste Management





This model fosters collaboration among Producers, Consumers, the Government, and PROs to manage solar panel waste efficiently. Producers supply panels to consumers, supported by government subsidies to promote green energy. Consumers hand over end-of-life panels to PROs, which collect, recycle, and refurbish materials. The government supports PROs with tax incentives, transportation aid, and advanced recycling technology, enforcing penalties on producers for non-compliance. Extended Producer Responsibility (EPR) mandates producers to meet recycling targets, linking them with PROs. Recycled materials re-enter production or are consumed by allied industries, while refurbished panels serve low-energy needs, achieving a circular, resource-efficient economy.

Financial Benefits

- Reduces the cost of raw materials for producers by reusing recycled components, lowering production costs.
- Creates economic opportunities for PROs and allied industries through the sale of recycled materials.
- Government subsidies encourage solar panel adoption, boosting green energy markets.
- Lower costs for consumers in rural and semi-urban areas through refurbished solar panels.

Environmental

- Minimizes e-waste by ensuring proper disposal and recycling of solar panels.
- Reduces reliance on virgin raw materials, conserving natural resources and lowering carbon footprints.
- Prevents hazardous materials in solar panels from polluting soil and water systems.

Efficiency

- Promotes sustainable practices by enabling a closed-loop system for material reuse.
- Ensures resource equity by directing refurbished panels to underserved areas.
- Encourages innovation in recycling technologies through government-supported PROs.

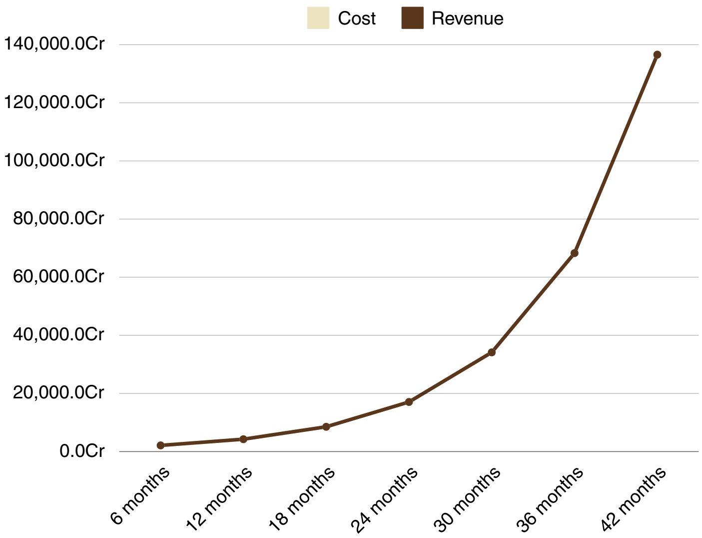
Cost Benefit Analysis

CBA for Machinery

To assess the economic feasibility of establishing solar panel recycling plants in India, a detailed CBA has been conducted. This analysis evaluates the financial viability of the setup and operations by estimating revenues from recovered materials and associated costs.

Overview of Project

- Number of Plants: 5
- Capacity per Plant: 1000 kg/hour
- Objective: Recycling solar panel waste to recover valuable materials (silver, aluminum, copper, and silicon) and achieve economic and environmental sustainability.



Breakeven

Cost Analysis

The cost analysis focuses on the major costs associated with setting up and operating the recycling plants, which include:

- Capital Investment
  - Setup Cost per Plant: **₹ 2.28 Cr**
  - Covers: Machinery, facility setup, and equipment.
- Operating Costs
  - Monthly Variable Cost per Plant: **₹ 355.58 Cr**
  - Includes: Labor, electricity, transportation, maintenance, and raw material processing.
  - Cost per ton is estimated based on industry standards for solar waste recycling.

For a more accurate financial outlook, factors like local conditions, depreciation etc., should also be factored into the overall CBA.

Benefit Analysis

Revenue is primarily generated from selling the recovered valuable materials from the recycling process.

- Revenue Generation
  - Monthly Revenue per Plant: **₹ 355.64 Cr**
  - Generated from selling recovered materials (e.g., silver, aluminum, copper).
  - Revenue calculations consider material recovery yields and current market prices.
- Profitability
  - Net Monthly Profit per Plant: **₹ 6.66 L**
  - Breakeven Period: **34.24 months** (approx. 2.85 years).

Key Insights

1. Economic Viability
   - Recycling solar panels is a profitable venture due to the high value of recovered materials, especially silver and aluminum.
2. Scalability
   - With an expected rise in solar panel waste, the scalability of these recycling plants offers substantial economic and environmental returns.
3. Market Sensitivity
   - Profitability is highly dependent on market prices for recycled materials. A 10% drop in the price of silver or aluminum could significantly impact revenues.
4. Technological Advancements
   - Improved recycling technologies could enhance recovery rates and lower costs, boosting profitability further.

Key Indicators

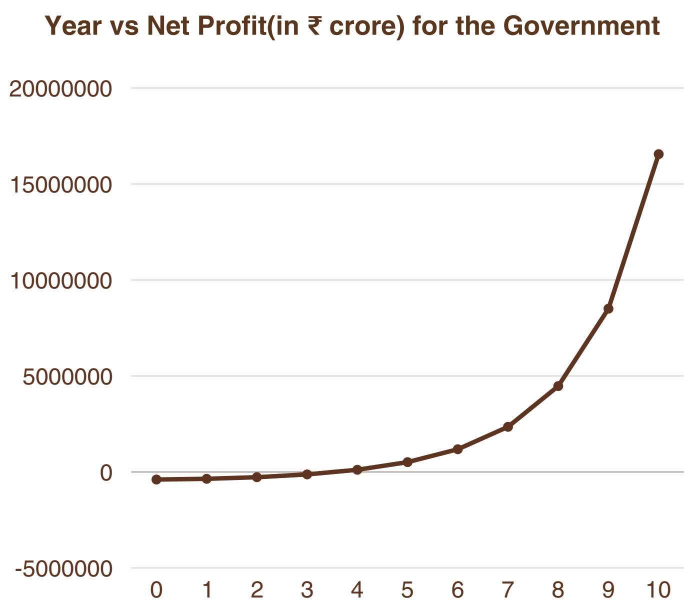
1. **Net Profit (Benefits - Costs):** Initially negative due to high upfront costs, the **break-even point** occurs **between years 3 and 4**, as net profit shifts from negative to positive. By year 10, the net profit is **₹1,65,54,102 crore**.
2. **Job Creation:** Over **1.75 crore jobs** are created by **year 10**, with 100 workers per plant (5 plants) earning ₹20,000 annually, contributing to GDP growth.

This analysis shows that while initial costs are high, the policy achieves profitability in year 4, sustained economic growth, and environmental benefits, making it a viable long-term initiative.

Benefits

The policy generates benefits of **₹7,500 crore annually**, derived from:

1. **Trade Revenue (₹600 crore):** Export of recovered materials like silicon and metals.
2. **Environmental Savings (₹400 crore):** Avoided disposal and pollution costs.
3. **Economic Growth and Circular Economy Development (₹3,000 crore):** Boost from material reuse and economic activities.
4. **Cost Savings for Manufacturers (₹500 crore):** Lower input costs.
5. **Revenue from Penalties and Activities (₹3,000 crore):** Enforcement-driven income and downstream economic activities.



CBA for Policy Formulations

The **Cost-Benefit Analysis (CBA)** evaluates the implementation of a solar panel recycling policy in India, focusing on costs, benefits, and socio-economic impacts over 10 years. The policy addresses the end-of-life management of solar panels to promote sustainability, economic growth, and environmental benefits.

The annual cost is **₹10,01,130 crore**, largely driven by skill development programs (**₹10,00,000 crore**), followed by operational costs (**₹300 crore**), capital investment (**₹200 crore**), incentives/subsidies (**₹200 crore**), and other administrative and enforcement costs. A one-time cost of **₹180 crore** is allocated for setting up the framework.

Appendix

Appendix A:

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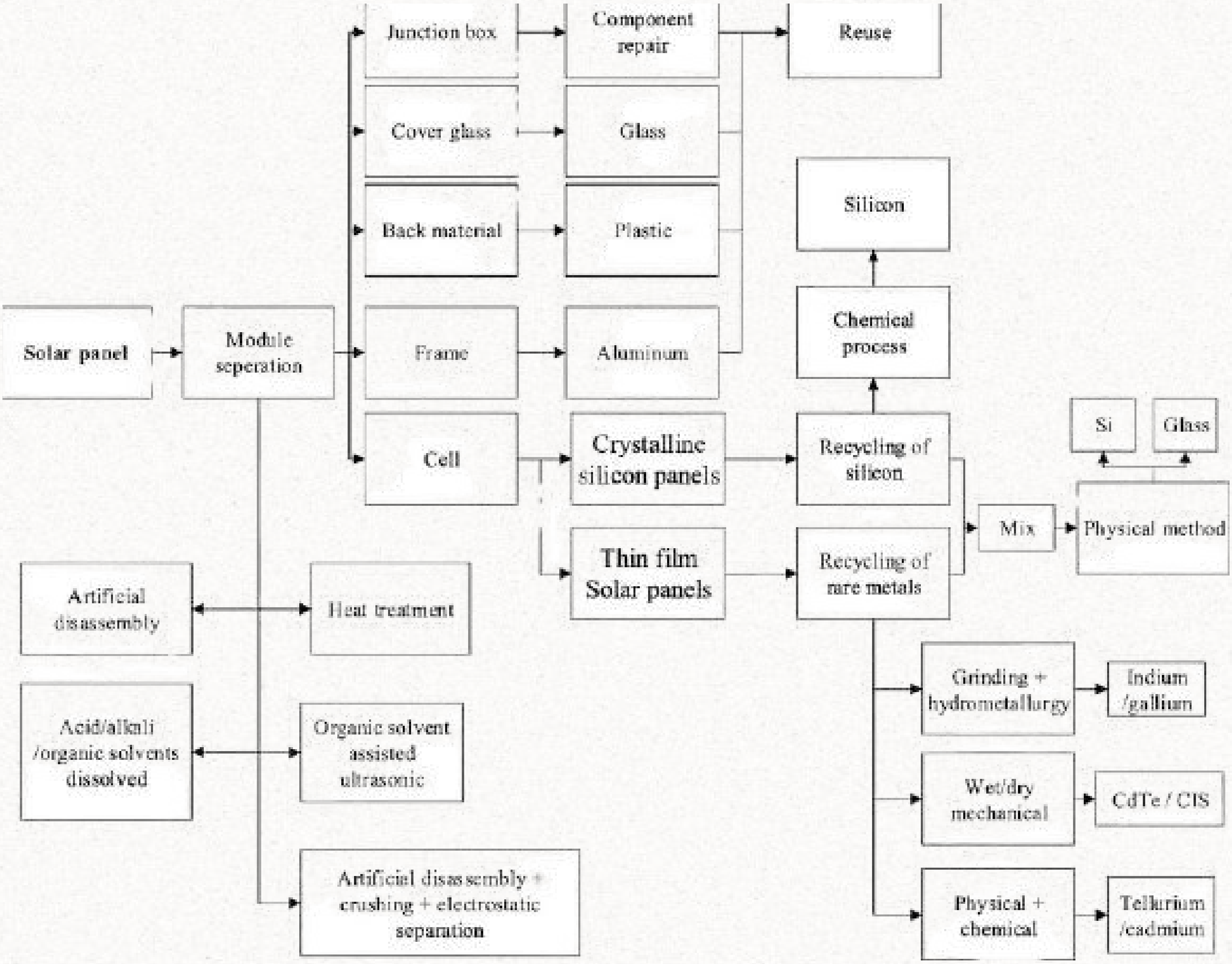
- https://pubs.acs.org/doi/full/10.1021/acssuschemeng.6b00894?casa_token=r0ta43I9dmcAAAAA%3AJUCJkBQIGEanvIL8OaWFZ0UAsRtGkRJ5SohHj6a4gPy1RnjT7pV9sx1BRDfgwnuo0S1UpUmy-jWbLck (Recycling of precious metal from Solar Panel)
- https://www.sciencedirect.com/science/article/pii/S0927024822003932?casa_token=G2F4L-ZYgAQAAAAA:icYZvGsip7NNH7tMwympA6PxFrkkoLXyZUVyYEUTJRxj9RS75V1343u1ITQjY2kdhXfOIajQmbkv (part by part recycling)
- https://www.mdpi.com/2079-9276/13/12/169 (secondary treatment process)
- https://www.mdpi.com/2071-1050/16/13/5785 (Silicon recycling)
- https://www.sciencedirect.com/science/article/pii/S2212982021000445?casa_token=LnKywwapSXAAAAAA:eTw51VCHLr1zuJIUKZae5e_NwHKaUYK1AM1ck3Ktdu67Twb63RjITts-jkuvmp0H6SXq7_3lSg(Supercritical CO2)
- https://www.sciencedirect.com/science/article/pii/S0038092X18311794?casa_token=QFffTdSebGkAAAAA:JEYiSmZi0vOS6su_YS0Vs9FHnNrz5OfxC8ch2qeiEMO75mebck4Y30xpKhuohDbmFtYhXo6fag(Thinfilm cell recycling)
- https://ieeexplore.ieee.org/abstract/document/9528207(iot solution)
- https://www.emerald.com/insight/content/doi/10.1108/imds-11-2016-0489/full/pdf?title=iot-based-tracking-and-tracing-platform-fo
- https://journals.sagepub.com/doi/abs/10.1177/0734242X211003977(gaps in current infra)
- https://www.aims-international.org/aims17/17ACD/PDF/A302-Final.pdf(gaps in current infra)
- https://www.sciencedirect.com/science/article/pii/S0959652624011090(gaps in current infra)
- https://renewablewatch.in/2021/01/15/small-step-forward/(gaps in current infra)
- https://www.sciencedirect.com/science/article/pii/S2212827115000153(Hot Extrusion)

Step by Step Flow chart Analysis



This flowchart provides a detailed overview of the solar panel recycling process, specifically focusing on the treatment and recovery of materials from different components of solar panels, such as crystalline silicon panels and thin-film solar panels.

Appendix C:
Detailed calculation for cost benefit analysis

Cost Benefit Analysis for Recycling Infrastructure

Recycling Capacity	1000kg/h
Assuming recycling industry works for 12 hours in a day and considering 24 working days in a month	
Mass of solar panel will recycle in a month	288000 kg/month or 288 tonnes/month

Recyclable Material	Mass of material/ tonne of solar panel	Mass of material can be recycled in a month (in tonnes)	Recycling Yield (%age)	Recoverable mass of each material (in tonnes)	Cost of material (USD/tonne)	Revenue (in USD)	
Silver	0.05796	16.69248	95	15.857856	651000	10323464.26	
Aluminum	16.5579	4768.6752	100	4768.6752	2000	9537350.4	
Copper	0.73664	212.15232	100	212.15232	6460	1370503.987	
Tin	0.00006	0.01728	32	0.0055296	19340	106.942464	
Zinc	0.00001	0.00288	27	0.0007776	2610	2.029536	
Silicon	0.79531	229.04928	100	229.04928	29998	6871020.301	
Lead	0.0047	1.3536	98	1.326528	2320	3077.54496	
Nickel	0.00107	0.30816	41	0.1263456	14520	1834.538112	
EVA	6.51886	1877.43168	0	0	890	0	
Glass	65.84046	18962.05248	95	18013.94986	790	14231020.39	
					Total Revenue (in USD)	42338380.39	USD
					Total Revenue (in INR)	3556423952	INR

Electricity Cost Breakdown

Unit cost	7.5	Rs/ KWh
Machine power	195	KW
Working Hours	12	
Working Days	24	
Total Electricity Cost	421200	Rs.

Transportation Cost Breakdown

Distance for nearest plant	200	KM
Cost of transportation per km per tonne	7.5	INR
Plant capacity per month	288	Tonnes
Total transportation cost	432000	INR

Raw Material cost breakdown

Plant capacity per month	288	
Cost of Solar Panel Waste per KW	2.26	$
Cost of Solar Panel Waste per KW	189.84	INR
Cost of Solar Panel Waste per MW	189840	INR
Cost of Solar Panel Waste per Tonne	12339600	INR
Total Cost of Raw Material	3553804800	

Detailed Business Figures

Recycling unit cost (Machinery)	1.93 Crore	One time
Factory setup cost (Machinery Transportation, installation,etc.)	Approx. 10 Lakhs	One time
Average Licensing fees	Approx. 25 lakhs	One time
Land Rent	700000	Monthly (in INR)
Labour Cost	400000	Monthly (in INR)
Electricity Cost	421200	Monthly (in INR)
Transportation Cost	432000	Monthly (in INR)
Raw Material Cost	3553804800	Monthly (in INR)
Total Variable Cost per Month	3555758000	INR
Fixed One time cost	22800000	INR
Net Profit for one month	665952.42	INR
Time to reach break even	34.23668015	months

Assumptions and GDP Contribution on Job Creation

Assumptions	Assigned Values	Year	GDP % Growth	Job Creation	Net Profit (Benefits-Costs) in Rs. Crores
Estimate number of Recycling Plant	5	0	2.50%	600000	-393630
		1	2.66%	637980	-355650
Number of Workers/ Plant	20	2	3.01%	721304.5837	-272325.4163
		3	3.61%	867133.8374	-126496.1626
Total Number of Workers	100	4	4.62%	1108432.852	114802.8523
		5	6.28%	1506567.028	512937.0283
Wages of each worker	20000	6	9.07%	2177325.414	1183695.414
		7	13.94%	3345908.336	2352278.336
Total Job creation amount	2000000	8	22.78%	5467144.465	4473514.465
		9	39.58%	9498671.641	8505041.641
		10	73.12%	17547732.83	16554102.83

Assumptions on Cost Parameter for Policy Implementation

- **Administrative Setup (₹30 crore annually):** Inspired by Swachh Bharat Mission, which allocated administrative budgets for national waste management. The value reflects the minimal yet necessary expenditure for policy implementation oversight.
- **Incentives/Subsidies (₹200 crore annually):** Derived from Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) incentives, which provided direct subsidies for green technologies. Similar amounts have been allocated for solar subsidies under schemes like PM KUSUM (Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan).
- **Monitoring Infrastructure and Enforcement Mechanisms (₹150 crore and ₹50 crore annually):** Inspired by National Green Tribunal (NGT) and pollution monitoring initiatives under National Clean Air Programme (NCAP), which allocate similar amounts for compliance and monitoring infrastructure.
- **Skill Development Programs (₹10,00,000 crore annually):** Based on Pradhan Mantri Kaushal Vikas Yojana (PMKVY), which allocated large sums for skill development in renewable energy and industrial sectors. The high value reflects nationwide training for a new, specialized workforce.
- **Capital Investment (₹200 crore annually):** Values drawn from the infrastructure investments under National Solar Mission for plant setups and green industrial zones.
- **Operational Costs (₹300 crore annually):** Inspired by operational budgets under Solid Waste Management Rules, 2016, which emphasize operational costs for waste segregation and recycling processes.

Assumptions on Benefits Parameter for Policy Implementation

- **Trade Revenue from Exports (₹600 crore annually):** Based on India's material recovery and export revenues from programs like E-Waste (Management) Rules, 2016, which regulate recycling and exports of electronic waste.
- **Environmental Savings (₹400 crore annually):** Inspired by Perform, Achieve, and Trade (PAT) scheme under the National Mission for Enhanced Energy Efficiency (NMEEE), which quantified cost savings from energy and pollution reduction.
- **Revenue from Penalties (₹500 crore annually):** Drawn from the penalties collected under EPR laws in Plastic Waste Management Rules, 2016, where non-compliance generates revenue that is reinvested into waste management systems.
- **Economic Growth (₹2,000 crore annually):** Inspired by reports from National Solar Mission and International Solar Alliance, which showcase the economic multiplier effects of renewable energy expansion.
- **Circular Economy Development (₹1,000 crore annually):** Based on insights from National Action Plan on Climate Change (NAPCC), which integrates circular economy models into sustainability goals.
- **Cost Savings for Manufacturers (₹500 crore annually):** Similar to savings seen in industries participating in the Metal Recycling Policy, 2019, which promotes secondary raw material usage.
- **Economic Activity (₹2,500 crore annually):** Inspired by economic impacts of large-scale initiatives like Make in India, which focuses on industrial activity and job creation.

GDP Growth (7.5%) and Wage Contribution (2.5%)

- **GDP Growth (6.33% annually):** Based on historical GDP growth rates during the rollout of renewable energy programs like the National Solar Mission, which significantly contributed to economic growth.
- **Worker Contribution to GDP (2.5%):** Inspired by the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), where wage payments to unskilled workers directly impact rural GDP contributions, reflecting the assumption here.

Cost Benefit Analysis for Policy Implementations

Cost Parameters	Costs Incurred annually (Rs. crore)	Benefits Parameters	Benefits annually (Rs. crore)
Administrative Setup	30	**Trade Revenue from Exports**	600
Incentives/Subsidies	200	**Environmental Savings**	400
Monitoring Infrastructure	150	**Revenue from Penalties**	500
Enforcement Mechanism	50	**Economic Growth**	2,000
Skill Development Programs	1000000	**Circular Economy Development**	1,000
Integration of Informal Sector	200	**Cost Savings for Manufacturers**	500
Capital Investment	200	**Economic Activity**	2,500
Operational Costs	300		
Total	1001130	**Total**	7500
One Time Cost	180		

Penalty-Reward System for Producer-Government-Consumer

X	Solar panel production cost for producer per unit
Y	Selling price to the consumer per unit
Z	Government subsidy to the consumer per panel
a%	Growth Rate of Solar panel adoption per year
b%	Percentage of Solar panel recycled per year
c%	Penalty percentage of missed target per year
d%	Tax credit as a percentage of the recycling cost if targets are fulfilled
e%	Discount offered on the new panel by the producer to consumers for exchanging old panels
f%	Rate of profit from Recycling to the producer
g%	GST from producers for manufacturing to the government
t	self life of panels
R	Recycling cost per panel

CONSUMER		
C_net =	Y-Z-e.Y'	Y' is the S.P. after t years
PRODUCER		
R_profit =	Y-X	
After Recycling		
R_profit ' =	Y-X-R+d.Y+f.R	If Recycling is done
R_profit '' =	Y-X-c.Y	If Recycling is not done
GOVERNMENT		
G_net =	-Z-d.Y+c.Y+g.Y	