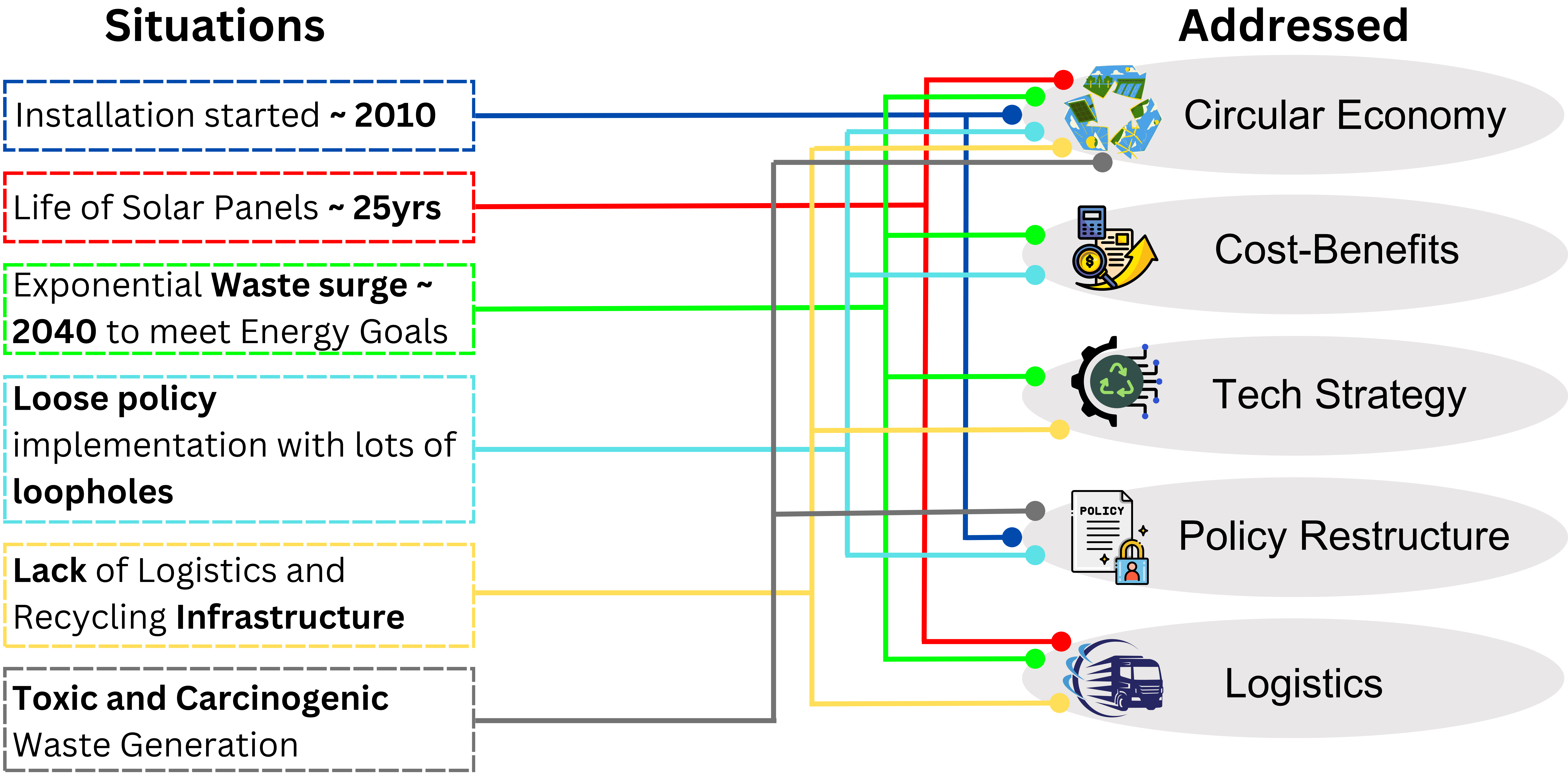
Problem Understanding



Prediction Model - Solar PV Module Waste

Inorder to predict the PV Module waste in India in the upcoming years we implemented two approaches - Mathermatical and Machine Learning model -SARIMA, to get to the most accurate prediction for building the frameworks ahead.

Mathematical Approach

Key Considerations

- EOL of a solar panel is considered when its efficiency reduces to **80% of the initial**
- At EOL modules would be decommissioned over a span of 5 years with **10%, 15%, 20%, 25%, and 30%** of the remaining capacity turning into waste annually.

Wastes

- Transportation Waste
- Product Operations Waste
- End-Of-Life Waste

Assumtions used (Based on Industry Std.):

- Solar panel installations = **until 2030**.
- Weight of solar panels = **65 tonnes per MW**.
- End-of-life (EOL) period = **25 years**.

Cummulative Waste Generated

$$Wc = Wth + \sum_{1}^{EoL-1} (Wpo) + \sum_{Eol}^{EoL+4} W$$

Under the above assumptions of solar installations cumulative PV module waste is estimated at **18,980 kilotonnes by 2050.**

**Inspired from: CEEW Report*

SARIMA Approach

We implemented the SARIMA Model to predict the waste generated by PV Modules.

Data Cleaning
Cleaned historical solar Panel installation records

»

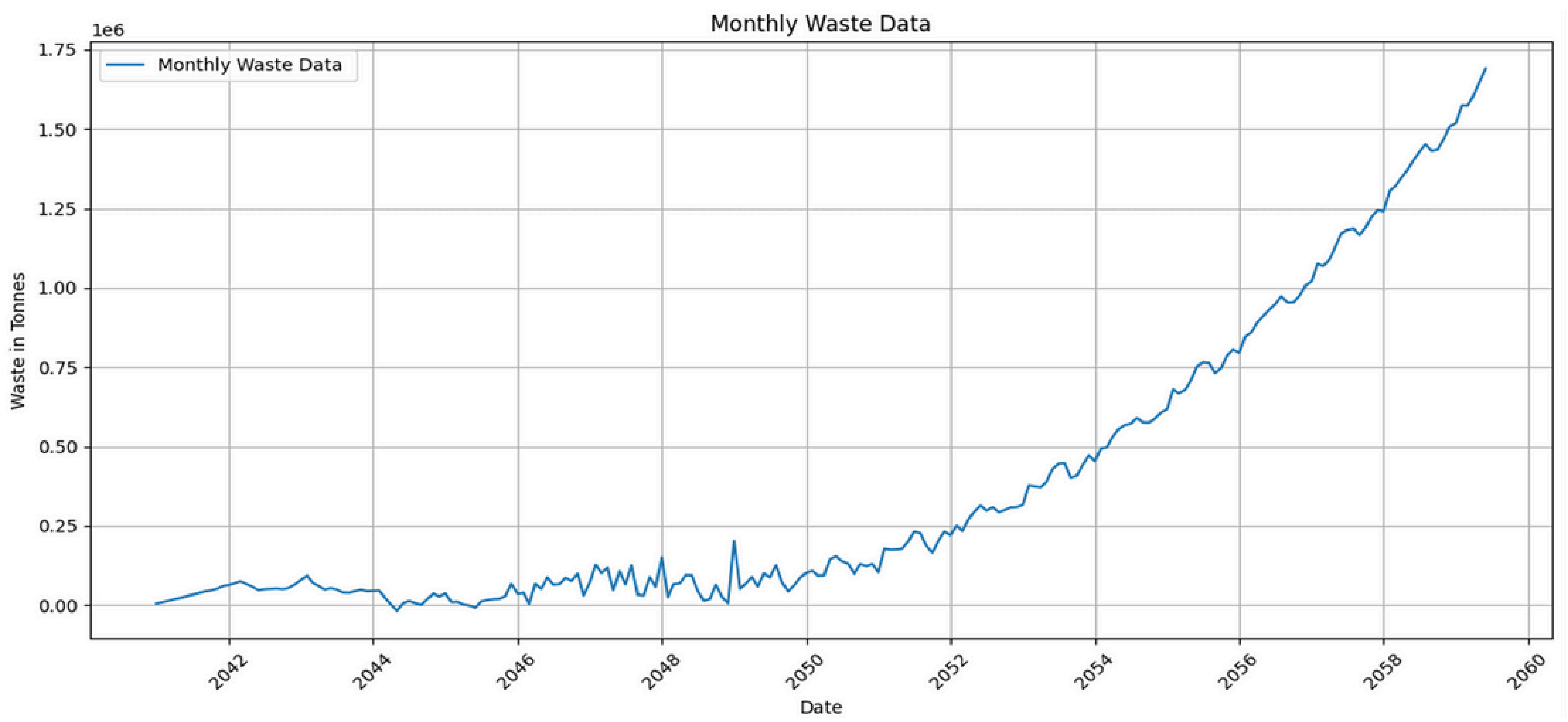
Stationarity Check
Applied ADF test and differencing methods

»

SARIMA Modeling
Forecasted trends using seasonal SARIMA parameters

»

Validation
Compared predicted data with actual observations



The cumulative waste generation by the Year 2056 is 84000 Kilo Tonnes.

By the SARIMA model the predicted cumulative PV module waste is estimated at **18061 kilotonnes by 2050.**

**Note: For detailed approach of both the models kindly refer chapter 2 of our report*

Environmental Impact

Pollution and Contamination

Landfills

The **least expensive pathways** by a wide margin.

Occupies large land areas, Leads to incorrect exploitation of natural lands, in addition to the emissions of various materials over time, especially with factors like water precipitation.

Toxic Leakage

Heavy metal contamination of soil.
Hyperaccumulation in plants
Leaching

- **Lead:** Impairs intellectual development, Damages brain, nerves, blood, kidneys, and reproduction.
- **CdTe:** Harms kidneys, liver, bones, and lungs; linked to lung cancer.

If not responsibly managed, they
(a) pollute our terrestrial ecosystem,
(b) indirectly encourage continuous mining and extraction of Earth's finite resources,
(c) diminish the net environmental benefit of harvesting solar energy

Resource Recovery

Using the results of our predictive model we estimated the quantities of recovered materials by 2050

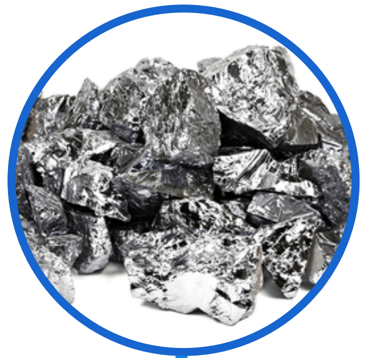
Material Constituent	Amount Recovered by 2050	Economic Value of Recovered materials
Aluminum	3,39,74,20,000 Kg	₹ 7,02,75,63,27,000.00
Cadmium	N/A	N/A
Copper	8,35,12,000 Kg	₹ 71,82,03,20,000.00
Silicon	66,61,98,000 Kg	₹ 1,12,66,74,05,760.00
Tin	N/A	N/A
Silver	96,79,800 Kg	₹ 9,13,10,52,13,800.00
Glass	12,62,17,00,000 Kg	₹ 2,52,43,40,00,000.00
Polymers and Plastics	77,81,80,000 Kg	₹ 42,79,99,00,000.00

Through our calculation the total amount in today's value of the recovered material **by 2050** would be **24.7 Billion Dollars** with recycling **efficiency being 92%**

**Note: For detailed Material Recovery Calculations kindly refer chapter 3 of our report*

R&D Before Recycling Technology

Significant R&D efforts in photovoltaics are focusing on designing for circularity to make recycling less intensive:

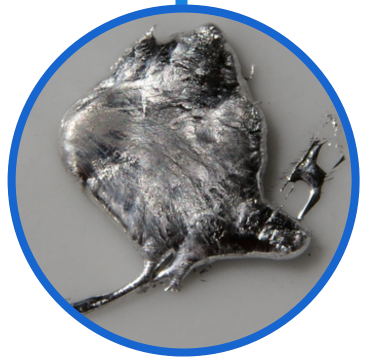


Silicon

Thinner cells and back-contact designs are being developed to halve silicon usage and cut energy consumption by around 30%.

Silver

Advances in inkjet and screen-printing, coupled with bifacial or rear-contact cell designs, aim to cut silver usage by 99% using nickel, copper, and aluminum.



Indium

Projects focus on replacing indium-tin-oxide (ITO) with fluorine-doped tin oxide to reduce indium reliance in thin-film PV technologies

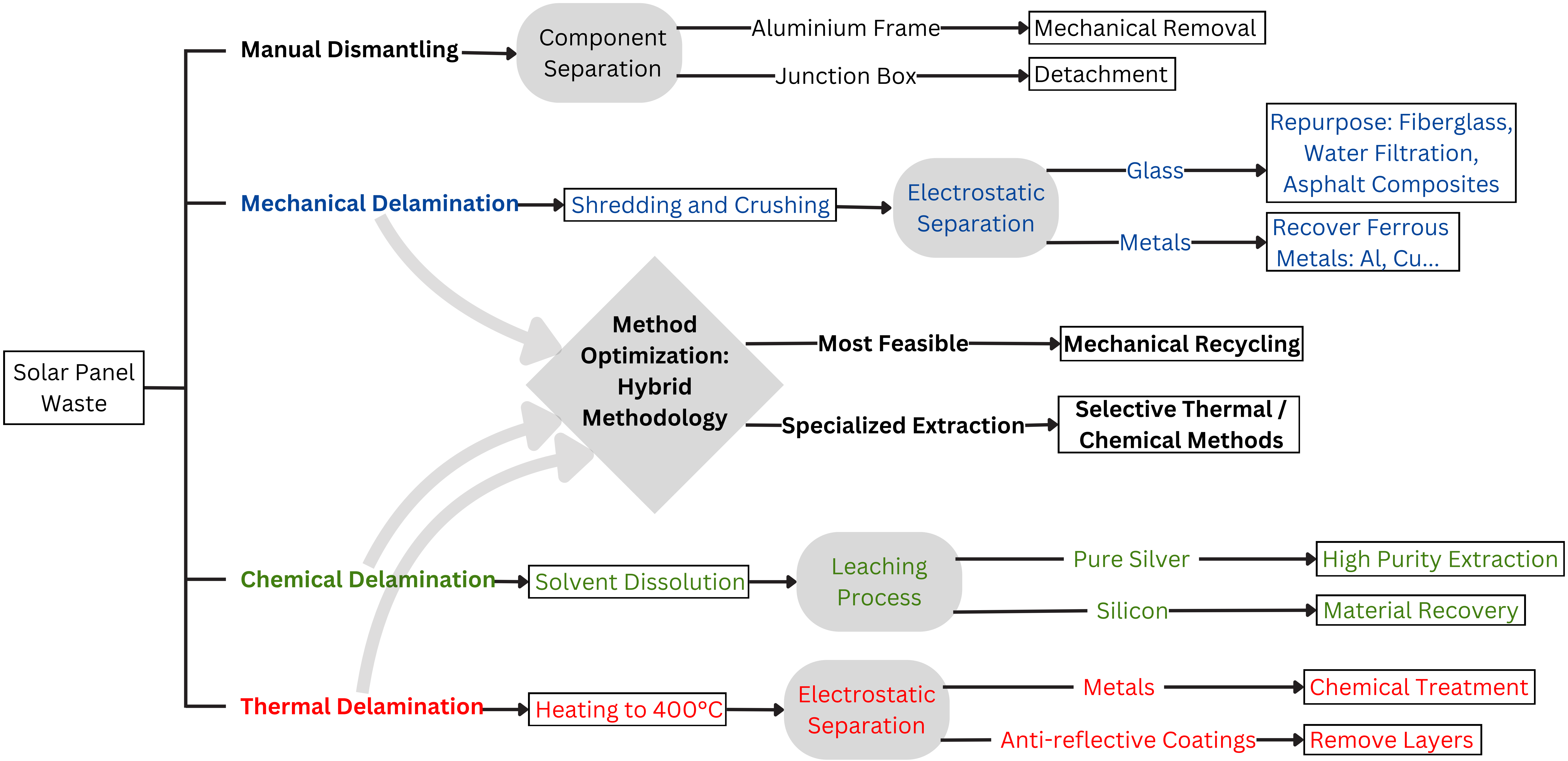
Polymer

Alternatives to non-recyclable encapsulants and backsheets include thermoplastics or designs eliminating encapsulants altogether.

Glass

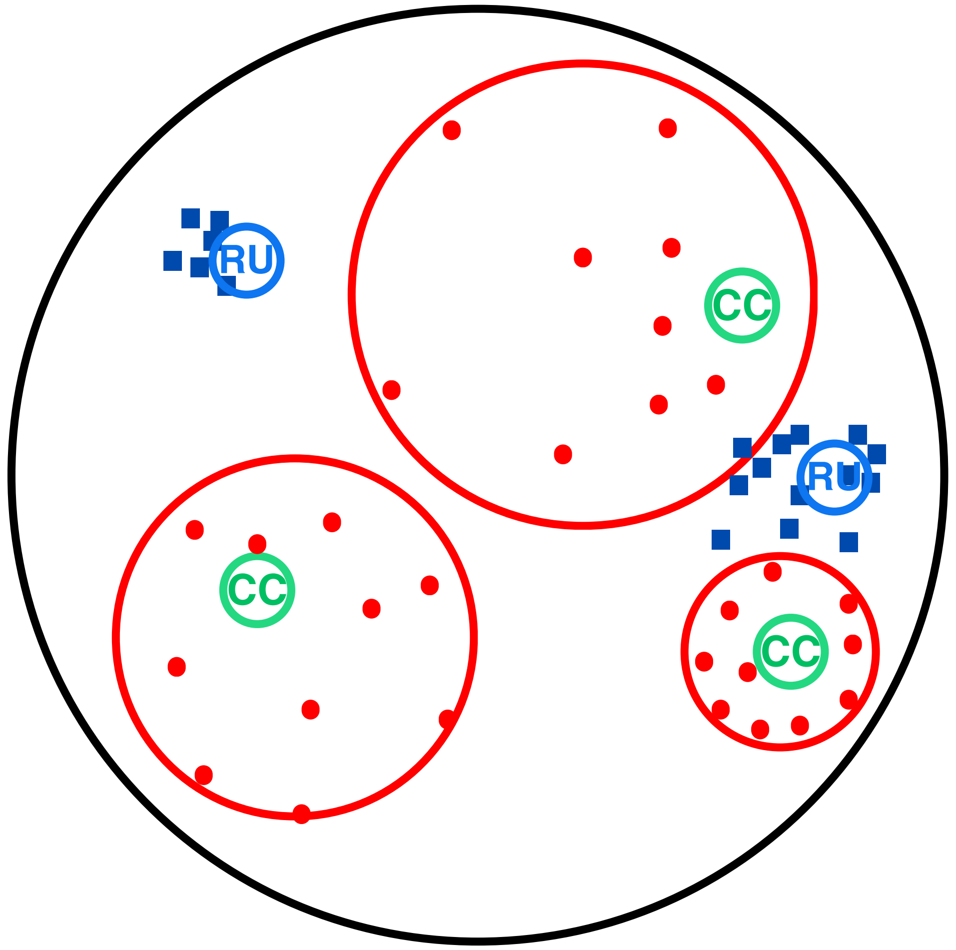
Innovations in glass composition, anti-reflective coatings, and double-glass panels improve light transmission and remove backsheets.

Recycling Technology



Logistics Framework

Logistics Model



Clusters are decided by common geography based on their cummulative installed capacity.

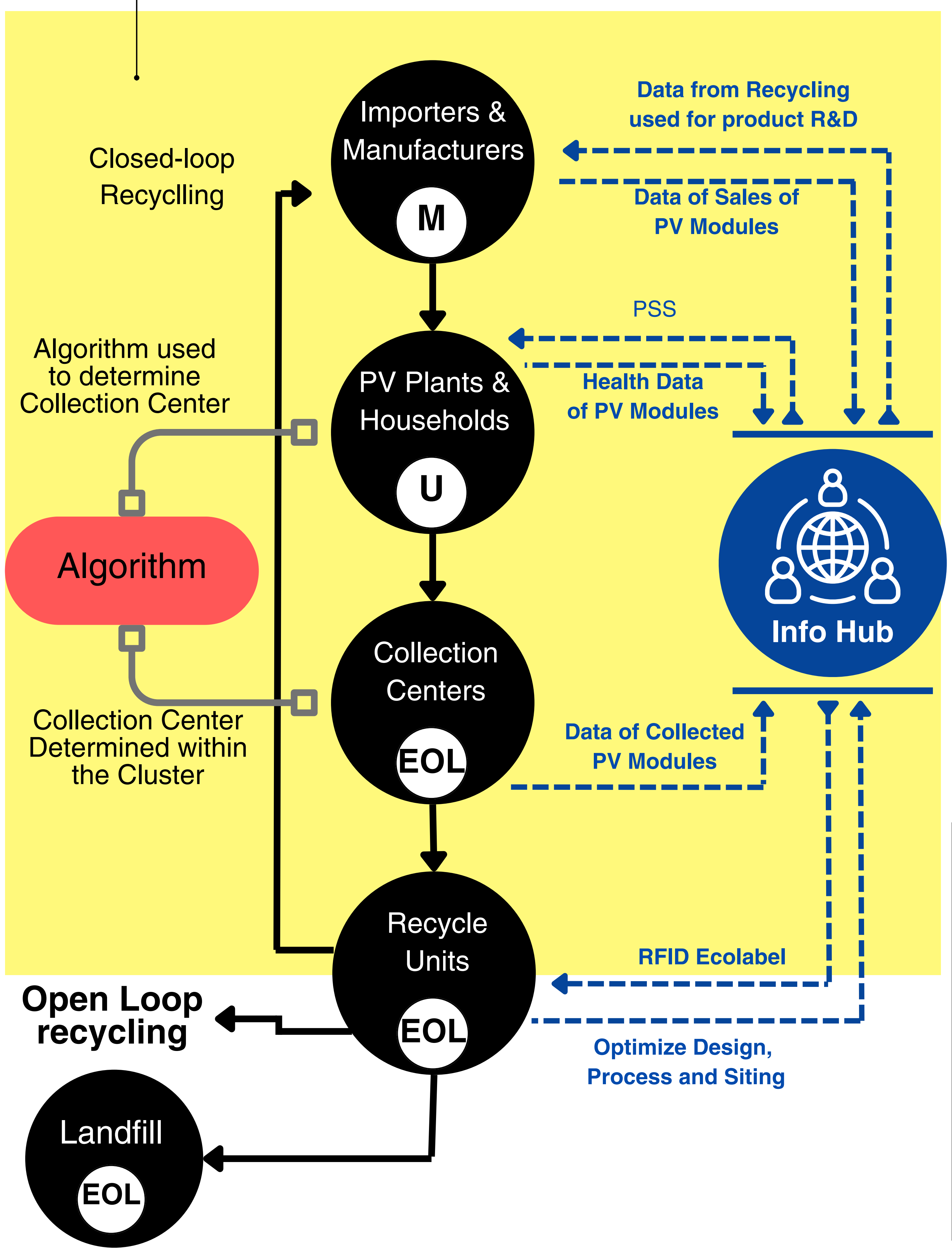
A **collection center** is designated PV plants that temporarily store end-of-life or failed panels.

Collection center is decided by **minimizing** the overall transportation cost within a cluster.

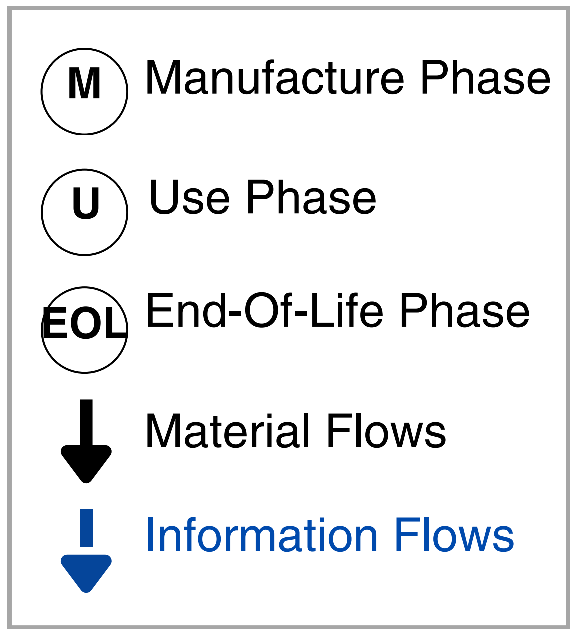
Recycling units are decided based on the close by industrial area and the transportation cost.

C **Clusters** > CC **Collection Centers** > RU **Recycle Units**

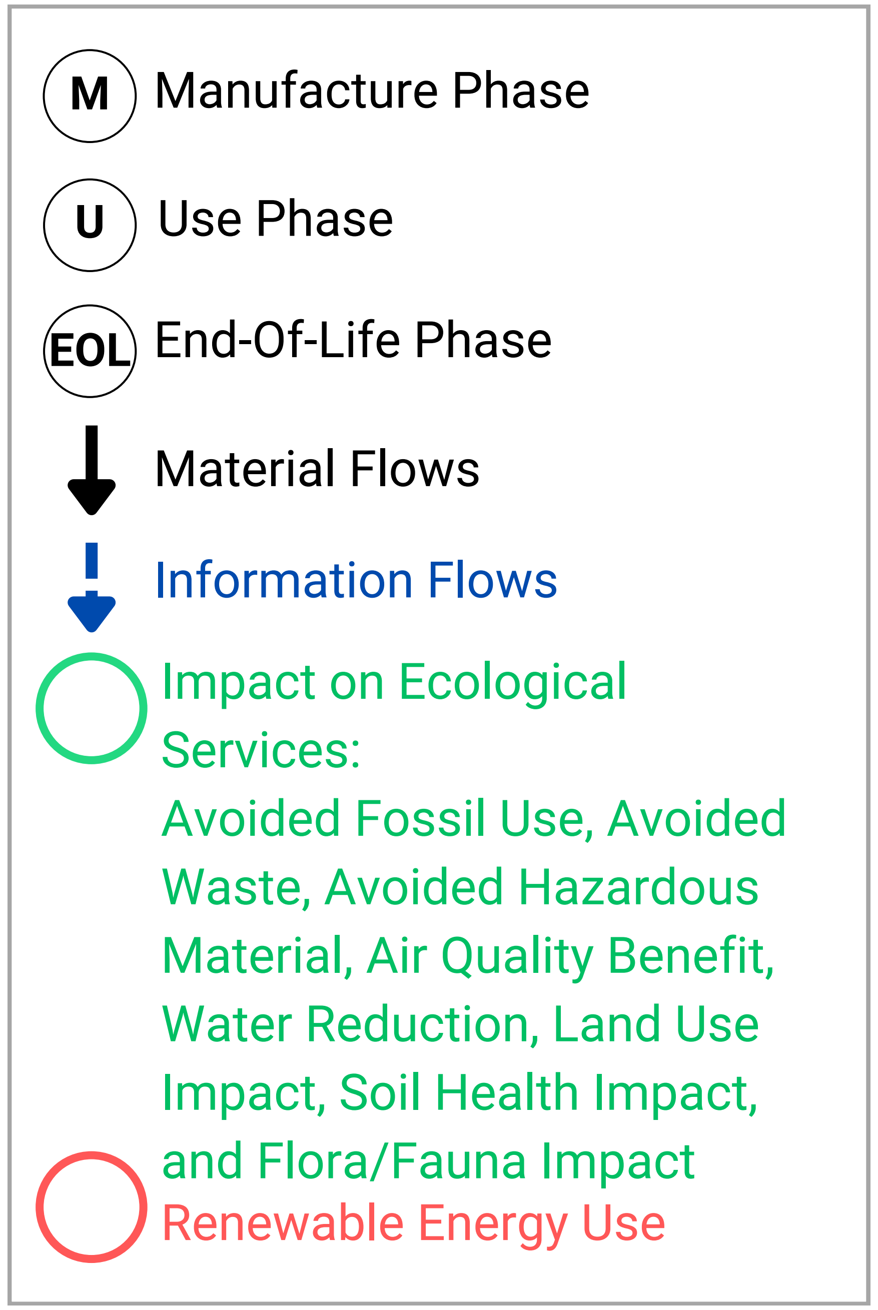
{Yellow region} indicates integration of **PROs** (discussed towards the end of section)

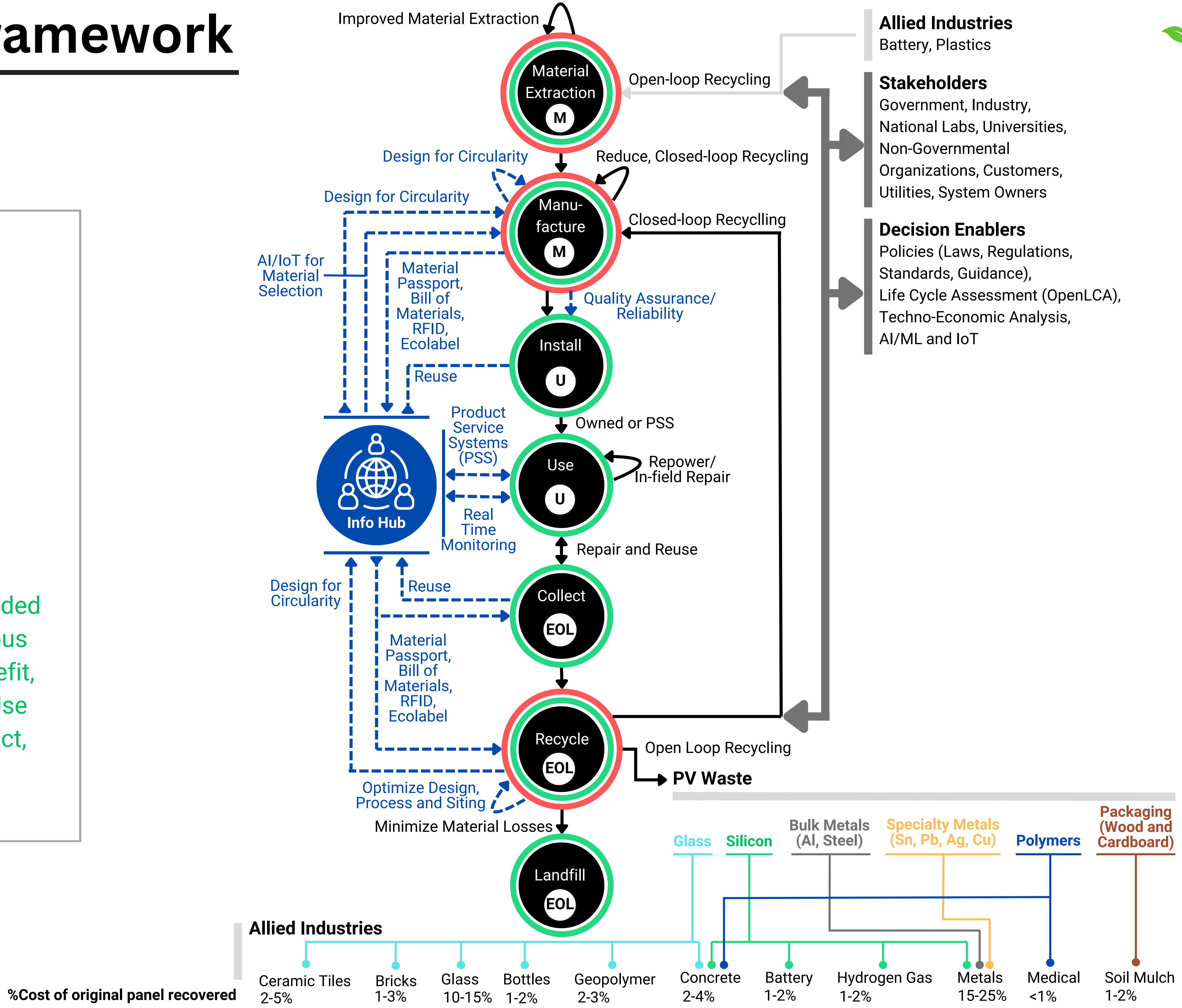


Material and Information Flow Framework



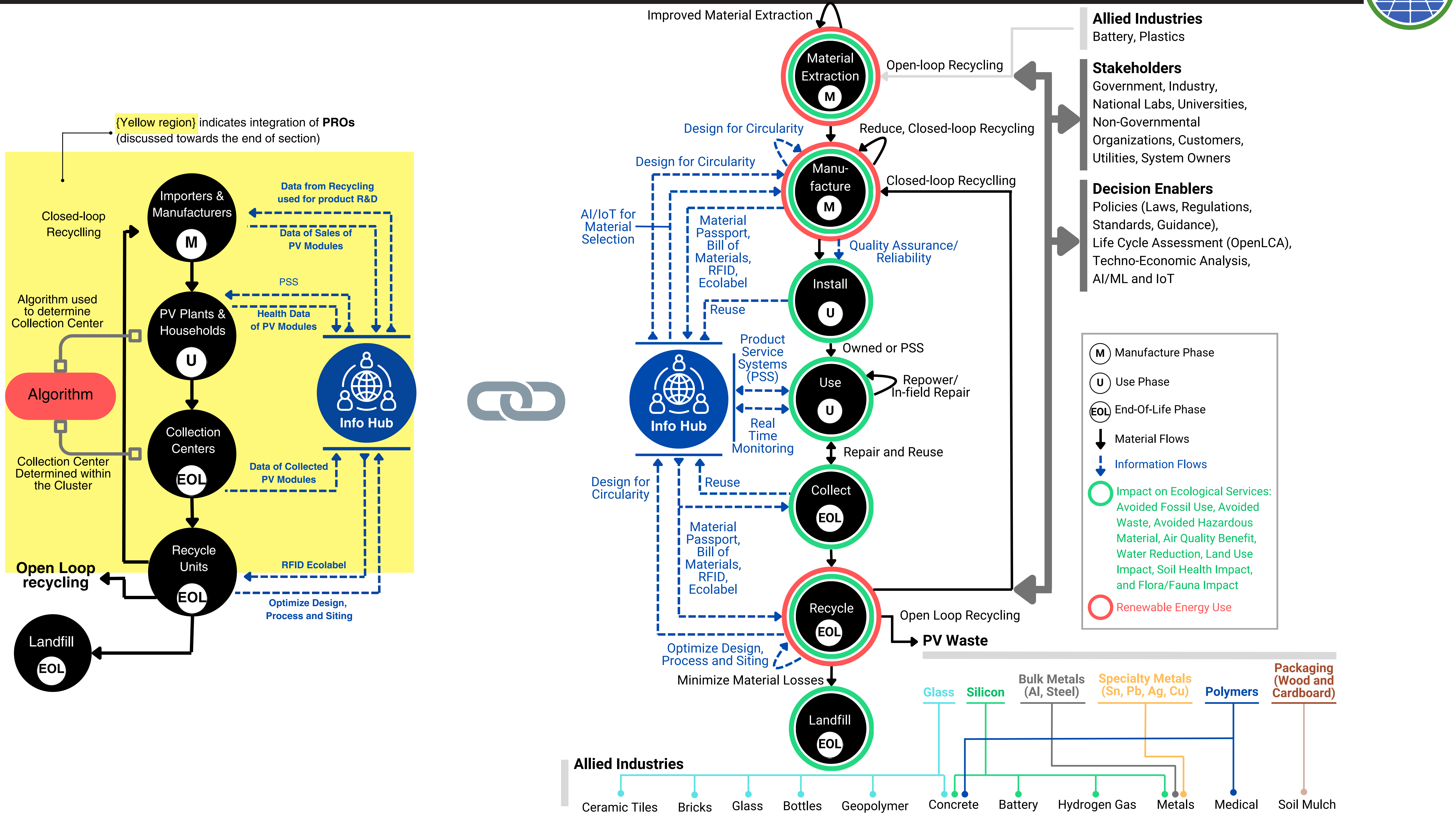
Circular Economy Framework



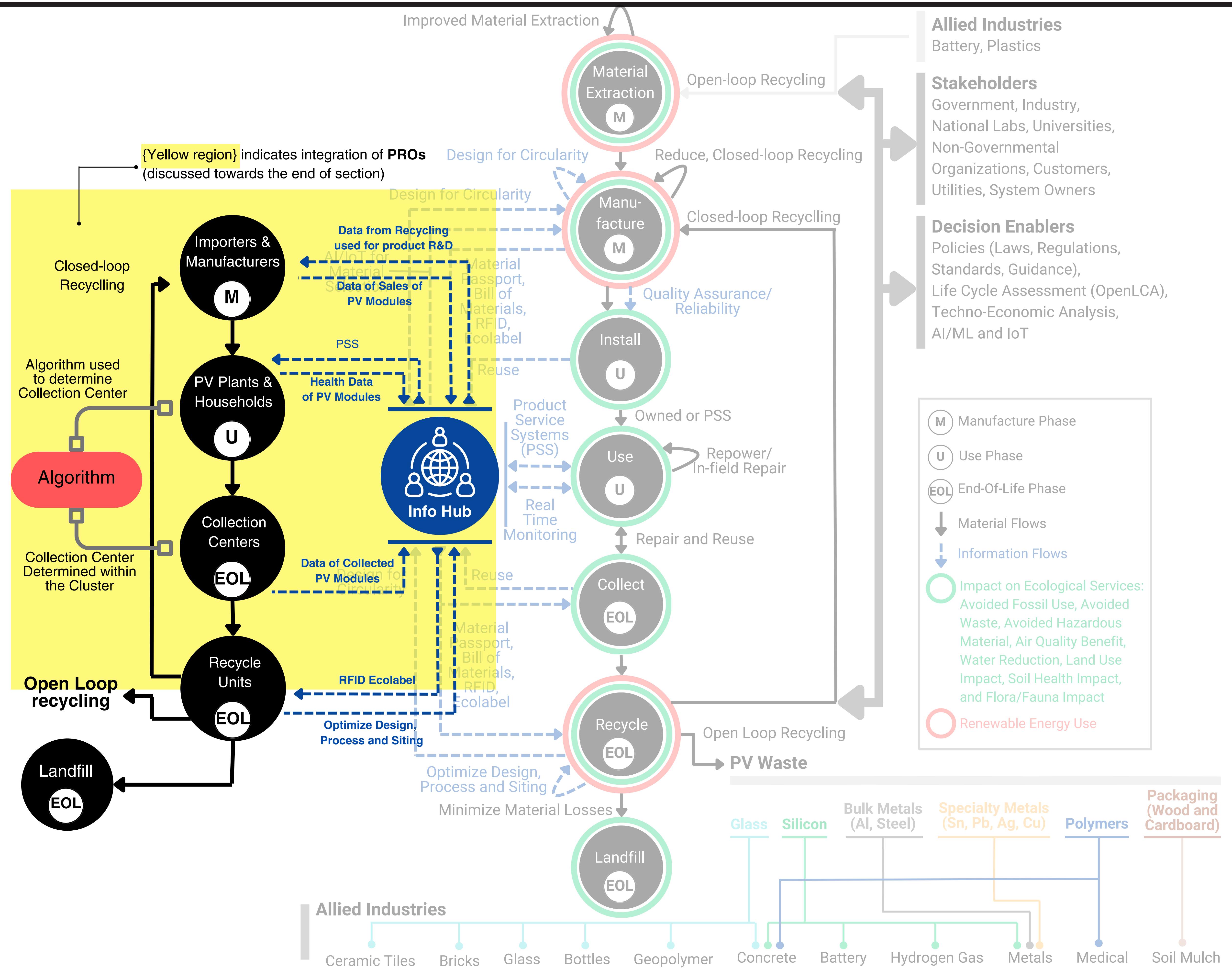


**Note: The circular economy model has been inspired from NREL Report.*

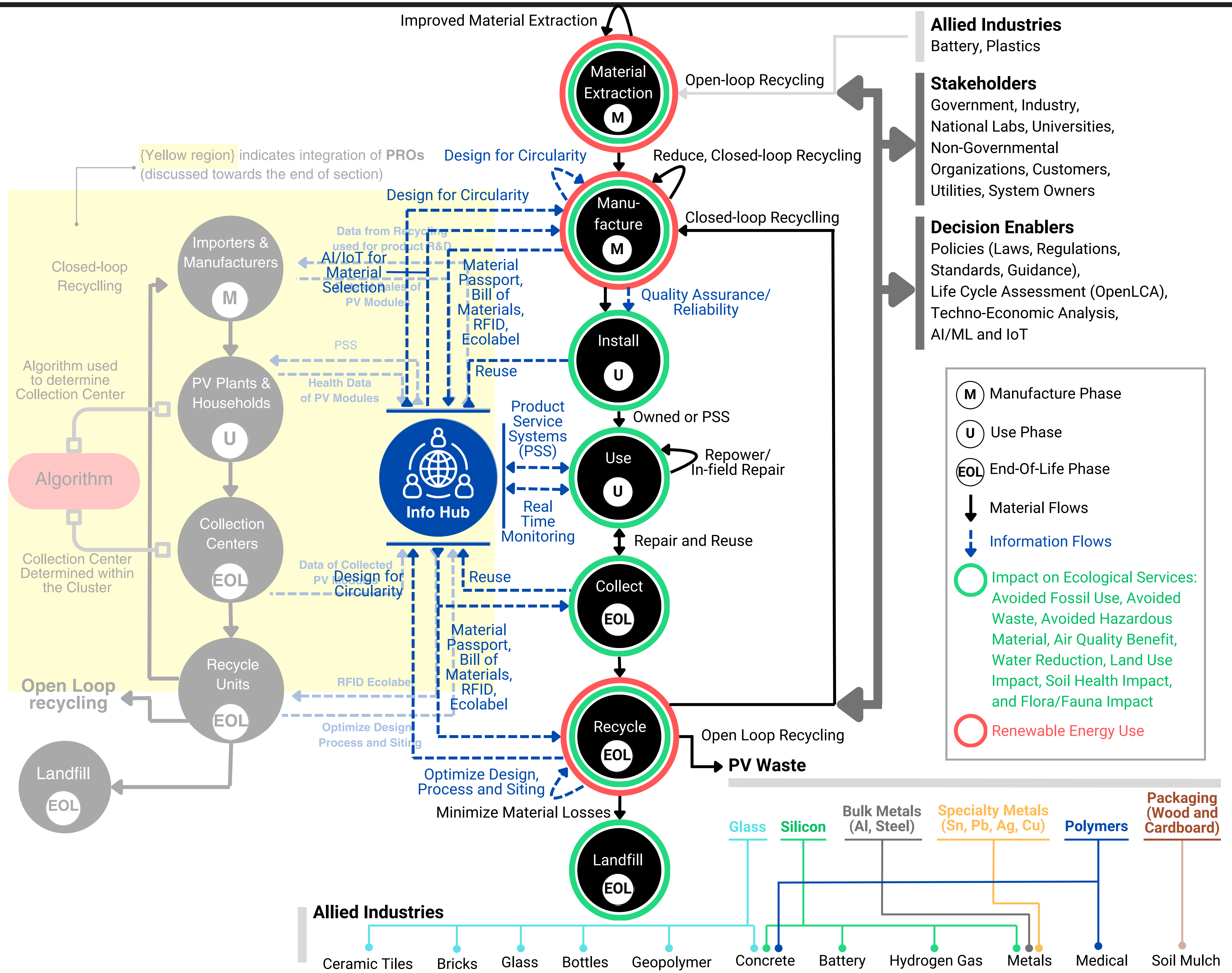
Logistics Circular Economy Framework



Logistics Circular Economy Framework



Logistics Circular Economy Framework



Policy and Regulatory Framework

In India, a special policy or framework is **not designed** for PV waste.

Current scenario

Loopholes in current e-waste mangement rules

India identifies less e-waste categories, compared to developed nations. shows the lack of awareness in fully capturing the e-waste issue.

Vagueness and absence of managerial regulatory framework in the collection.

India's EPR mainly focuses on downstream upstream measures are not mandated.

Loopholes in context to global scenario

India bans e-waste imports under 2016 Hazardous Waste Rules.
This ban is not absolute and can be bypassed legally or illegally.

Proposed Framework for India

A dedicated **Extended Producer Responsibility (EPR)** framework

Objectives as part of EPR can be achieved through various **policy measures**

UPSTREAM	MIDSTREAM	DOWNSTREAM
"Design for recycle"	"Creating demand for sustainable products"	"Prevent leakage into informal sector"

Mandate to recycle **80-85%** of module & **100%** of heavy metal

Instruments for implementation:

POLICY: product take back, minimum recycle requirements

ECONOMIC: Deposit/Refund, ECO Tax, Material Tax

SOCIAL: Product Labelling, Awareness Creation

Incentivizing potential stakeholders:

To **recyclers and waste collectors, recycling units, Producers and customers**

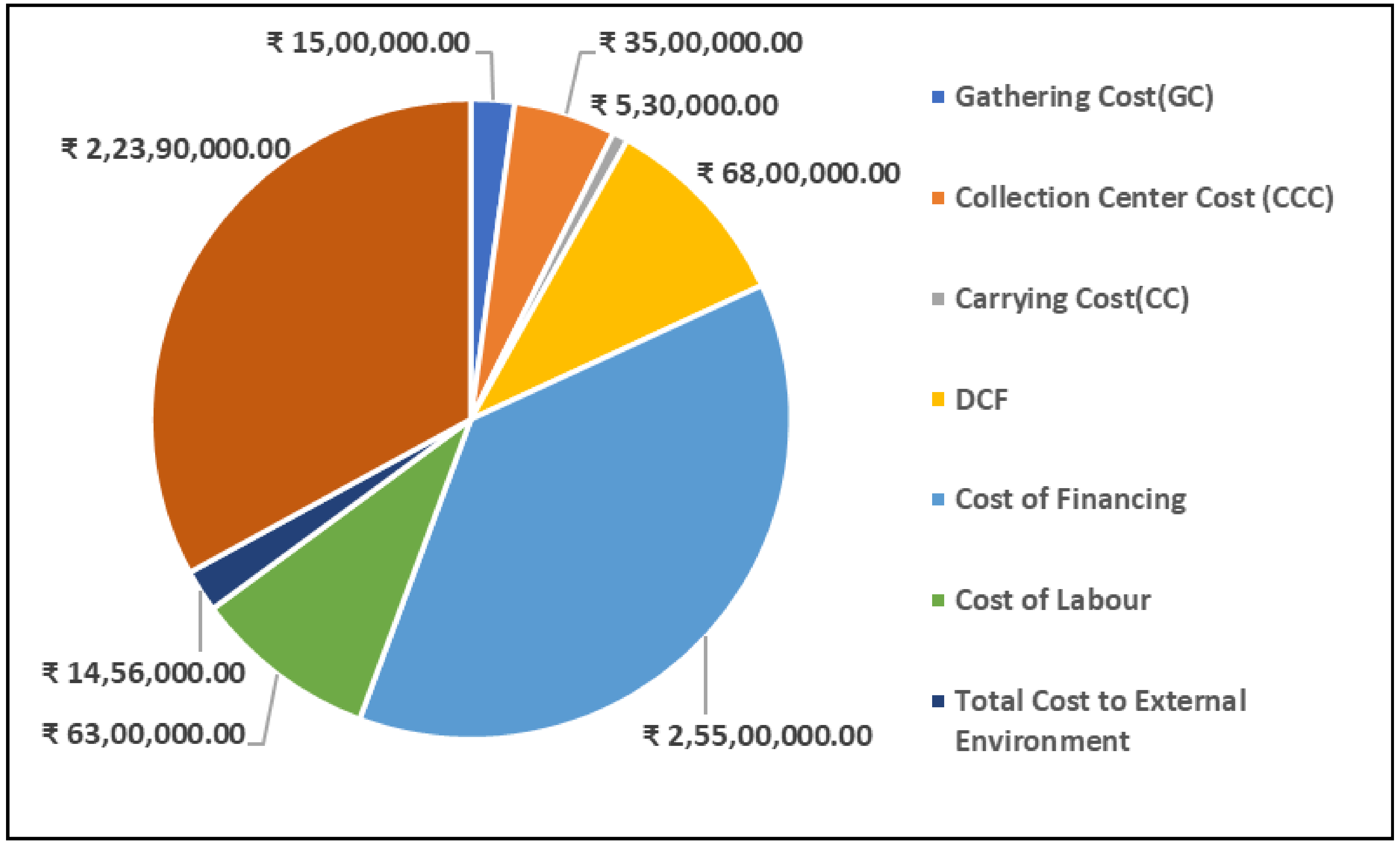
As **tax rebates, grants** for recycling units and **PSS** for customers

Cost-Benefit Analysis of PV Recycling

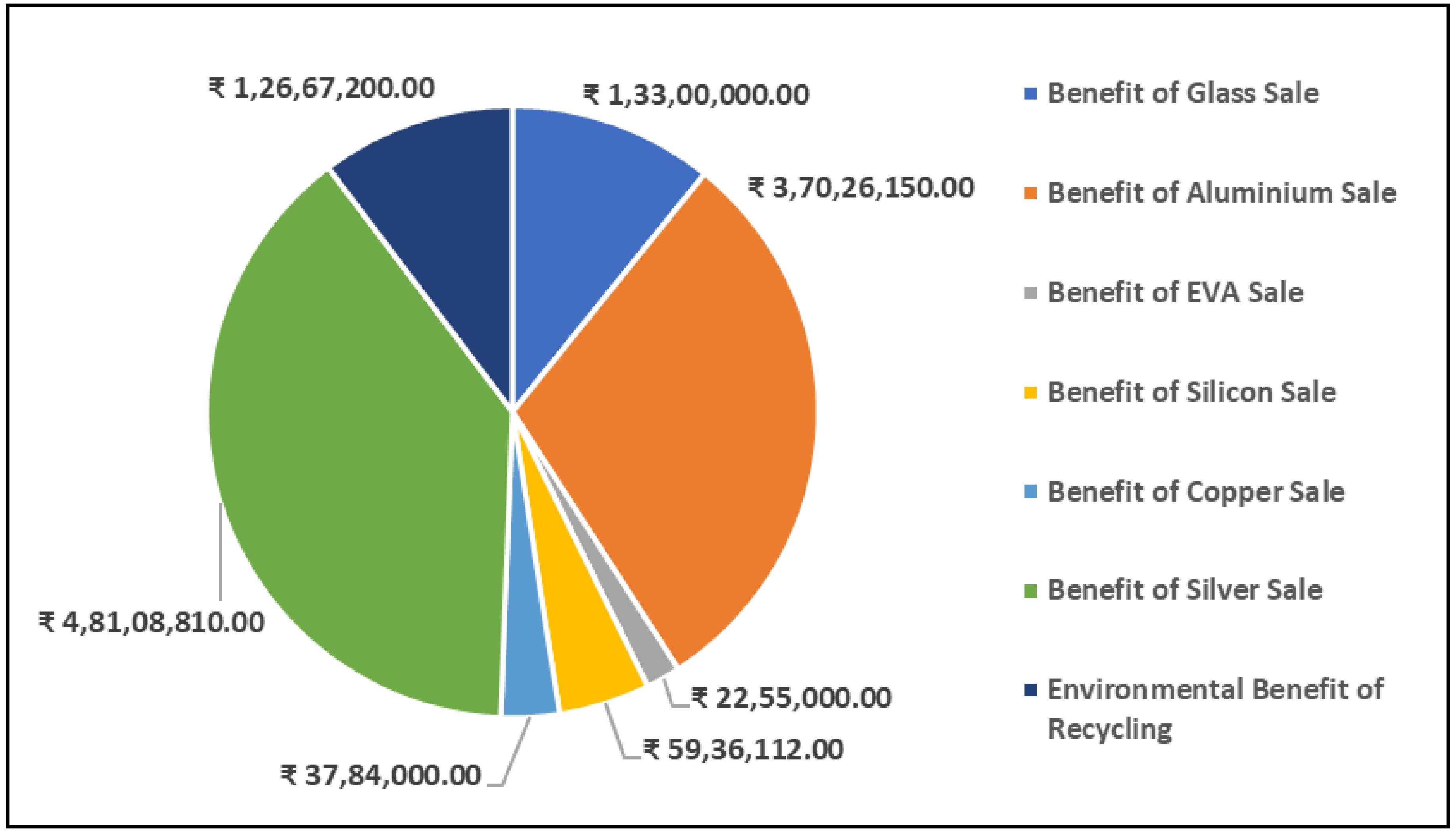
The Cost Benefit Analysis is based on considering basis as 1 Recycling Unit with a capacity processing **1000 Tonnes Per Year.**

(All costs and benefits are on per year basis for the plant.)

Cost



Benefit



Total Cost	Total Benefit	Net Present Value	Benefit-Cost Ratio
₹ 6.79 Cr per Annum	₹ 12.3 Cr per Annum	₹ 77.65 Cr	1.811

**Note: For detailed Cost Benefit Analysis kindly refer chapter 8 of our report*

Cost-Benefit Analysis of PV Recycling - Cont

Results:

- To encourage recycling unit investments, the government should offer **20% subsidies** and **tax exemptions**.
- Optimal transportation distance between the collection centers and recycling unit should be limited to **100-150 km.**

Social Benefits

Jobs Created by 2050	Carbon Emmisions Prevented	Material Recovered
38,120 Jobs	**33 Gt of CO_2 equivalent**	**176 Mt**

3-Phase Nation-Wide Infrastructure Plan

- **Phase 1 :** Establish 160 units with ongoing R&D.
- **Phase 2 :** Expand to 400 units by adding 240 more.
- **Phase 3 :** Add 800 units (total 1200) to handle peak waste generation.

Phases	Installed RU	Added RU
2025-2030	0-1	150-160
2031-2036	150-160	220-240
2036-2050	380-400	760-800

**Note: For detailed Cost Benefit Analysis kindly refer chapter 8 of our report*

Feasibility Report

Category	Suggestion	Feasibility Score (out of 10)			
		Economic	Technological	Indian Context	
Technology	End-to-end Mechanical Recycling with involvement for Chemical Recycling exclusively for production of EGS or for closed loop recycling.	8	10	9 Heat treatment will be more feasible in future when energy demands are met.	
Logistcs	Decentralization through cluster formation and optimizing transportation routes and economies though CCs and hiring PRO to take burden off producer's backs.	7	8	8	
Circular Economy	Incorporating local industries (open loop) and supply chain into an inter-linked framework with seamless material and data flow between different phases, locations and stakeholders.	10	7	8	
Policy	Dedicated and mandatory EPR for solar panel sector. Refund polices, minimum recycling policy, suggested incentives for different stakeholders	7	7	7 EPR policy suits for India, along with financial incentives to stakeholders.	