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Review on recycling of solar modules/panels

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ABSTRACT

A review article on recycling of solar PV modules, with more than 971GWdc of PV modules installed globally by the end of 2021 which includes already cumulative installed 788 GW of capacity installed through 2020 and addition of 183 GW in 2021, EOL management is important for all PV technologies to ensure clean energy solutions are a sustainable component of the energy economy for future generations.

With solar PV playing an increasing role in our global energy market, it is now timely and critical to understand the end-of-life management of the solar panels. Recycling the panels can be an important pathway, possibly recovering a considerable number of materials and adding economic benefits from currently installed solar panels.

Sustainable waste management offers opportunities known as the 3Rs: reduce, reuse, and recycle. When a product cannot be repaired or reused, recycling is the next preferable option before disposing as waste.

By 2050, 60 million tonne of solar waste will be there if it is not recycled properly. Their view offers an in-depth assessment and the various technical aspects of the solar panel waste recycling and recovery, environmental safety and waste control.

While the recycling of waste PV modules has already begun to be commercialized, various technologies for PV module recycling are under development in order to improve process efficiency, economics, recovery and recycling rates, and environmental performance.

1. Introduction

Solar panels have a lifetime of about 20–30 years [1–3]. With the increasing number of solar panels being sold and installed globally and due to the falling cost of solar has made renewable energy accessible to more people than ever before and has resulted in an exponential increase in solar adoption. With greater than 971GWdc of PV modules cumulatively installed globally in 2021, EOL management is important for all PV technologies to ensure clean energy solutions are a sustainable component of the energy economy for future generations (see Table 8–10 and 21, Fig. 32).

Within the coming years, excessive volumes of solar panels will be at the EOL and ought to be disposed of [4].

At the end of 2050, cumulative global PV waste streams are predicted to have reached 60–78 MT (see Figs. 1, 2 and 3), [5]. Increasing PV waste brings new environmental bottlenecks and unparalleled opportunities to generate value and seek new economic avenues. By 2030 the top three countries for cumulative projected PV waste are projected to include China, Germany and Japan [5].

In the United States, the SEIA initiated a national voluntary solar module recycling program in 2016. Most countries around the world classify PV panels as general or industrial waste, while the European Union (EU) has adopted PV-specific waste regulations [5].

EOL management could become a significant component of the PV value chain. Recycling PV panels at their end of life can unlock a large stock of raw materials and other valuable components. The recovered material inserted back into the economy can be distributed for the production of new PV panels or be sold into global commodity markets, thus increasing the security of future raw material supply [5].

EOL management for PV panels will spawn new industries, can support significant economic value creation, and is consistent with a global shift to sustainable long-term development.

PV EOL management also offers opportunities relating to each of the '3 Rs' of sustainable waste management.

- Reduce:

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Nomenclature

PV	Photovoltaic
EOL	End of life
IRENA	International Renewable Energy Agency
GWP	Global-warming potential
WEEE	Waste Electrical and Electronic Equipment
CdTe	Cadmium telluride
FRELP	Full recovery End-of-Life Photovoltaic
EVA	Ethylene vinyl acetate
Mono-Si	Monocrystalline silicon
Poly-Si	Polycrystalline silicon
CPV	Concentrator photovoltaic
a-Si	Amorphous silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
GaAs	Gallium arsenide
DSC	Dye-sensitised solar cell
HJT	Hetero-junction technology
BOS	Balance of system
RE-map	Renewable energy roadmap
GHG	Greenhouse gas
BSF	Back Surface Field
IEA	International Energy Agency
SEIA	Solar Energy Industries Association
MPPT	Maximum power point tracking
LT	Low tension
ACDB	AC distribution board
MCCB	Moulded case circuit breaker
TG	Thermogravimetry
JTP	Joined treatment program
WEEELABEX	Waste of Electronic and Electric Equipment Label of Excellence
DTSC	Department of Toxic Substances Control
OECD	The Organisation for Economic Co-operation and Development
LCIA	Life cycle impact assessment
LCA	Life cycle assessment
CSP	Concentrating solar power
BSF	Back surface field

Chemical Compounds

Ti	Titanium
Al	Aluminium
Cu	Copper
Ag	Silver
Pb	Lead
Si	Silicon
Sn	Tin
Zn	Zinc
Mo	Molybdenum
Se	Selenium
Ga	Gallium
In	Indium
Mn	Manganese
Mg	Magnesium
Ni	Nickel
Fe	Iron
Cd	Cadmium
Cr	Chromium
Te	Tellurium
As	Arsenic
Br_2	Bromine
H_2	Hydrogen
Pt	Platinum
$MAPbI_3$	Methylammonium lead iodide
TiO_2	Titanium dioxide
HNO_3	Nitric acid
H_3PO_4	Phosphoric acid
SiNx	Silicon nitride
KOH	Potassium hydroxide
Al_2O_3	Aluminium oxide
HF	Hydrofluoric acid
H_2SO_4	Sulfuric acid
PbO	Lead oxide
Ag_2O	Silver oxide
NaOH	Sodium hydroxide
$Al(OH)_3$	Aluminium hydroxide
$(N_2H_4{\cdot}H_2O)$	Hydrazine hydrate
Na_2S	Sodium sulphide
PbS	Lead sulphide
$Pb(OH)_2$	Lead (II) hydroxide
LIX84-I $_2$	hydroxy-5-nonylacetophenone oxime
$(CH_3)_2CO$	Acetone
PAH	Polycyclic aromatic hydrocarbon
HCl	Hydrochloric acid
NH_3	Ammonia
$Ca(OH)_2$	Calcium hydroxide
$CuSO_4$	Copper (II) sulphate
IrO_2	Iridium dioxide
AgCl	Silver chloride
Ag_2O	Silver oxide
$AgNO_3$	Silver nitrate
H_2O	Water

Units

µm	Micrometre
MT	Million tonne
eV	Electron volt
rpm	Revolutions per minute
GW	Gigawatts
GWdc	Gigawatts, Direct Current
Wp	Watt peak
EPBT	Energy payback time
Kg	Kilogram
$kgCO_2eq/kg$	Kilogram of carbon dioxide equivalent per kilogram
gCO_2 eq/kWh	Gram of carbon dioxide equivalent per kilowatt hours
DC	Direct current
KW	Kilowatt
A	Ampere
ml	millilitre
AC	Alternating current
°C	Degree Celsius
K	Kelvin
°C/min	Degree Celsius per minute
M	Molarity
Mins	Minutes
secs	Seconds
hr	Hour
g/L	Gram per litre
L	Litre
%	Percentage
mm	Millimetres
V	Voltage
I	Current
P	Power
W	Watts
W/m^2	Watt per square metre
min/cm^2	Minutes per centimetre square
mol/L	Moles per litre
$/kg	Dollar per kilogram
$/	Module Dollar per module

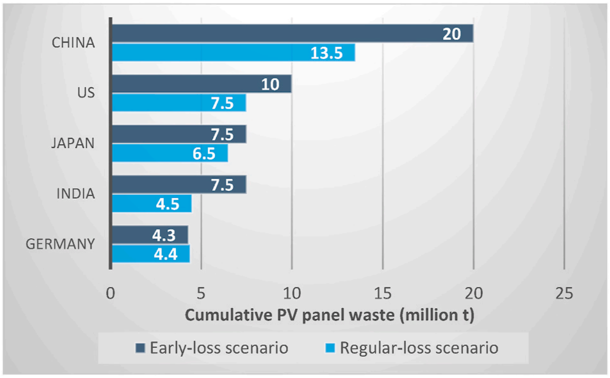

Fig. 1. Cumulative waste volumes of top five countries for of end-of-life panels in 2050 [5].

As research and development and technological advances continue with a maturing industry, the composition of panels is expected to require less raw material. This would reduce the use of hazardous and rare materials in the production process and consequently improve the recyclability and resource recovery potential of EOL panels.

- Reuse:

Rapid global PV growth is expected to generate a robust secondary market for panel components and materials. Early failures in the lifespan of a panel have repair and reuse opportunities. PV panels which are repaired can be resold on the world market at a lower market price.

- Recycle:

As current PV installations reach the final decommissioning stage, recycling and material recovery will be preferable to panel disposal. The developing PV recycling industry typically treats EOL PV panels through separate batch runs within existing general recycling plants. This allows for material recovery of considerable components. Examples include glass, aluminum and copper for c-Si panels that can be recovered at cumulative yields greater than 85% of total panel mass. In the long term, plants dedicated for panel recycling can increase treatment capacities and maximize revenues owing to better output quality and the ability to recover a greater fraction of embodied materials [5].

Recycling of solar panels is a success only if the materials used to manufacture them can be used again even after 30 years of usage. Solar panels are made from different components, including silicon solar cells, metal framing, glass sheets, wires, plexiglass. We know that many of the essential components of solar panels can be recycled on their own. Materials like metal, glass, and wiring can be reused and recycled. While silicon wafers are not recyclable like glass and plastic are, some specialty recycling companies are able to reuse silicon cells by melting them down and recovering the silicon and various metals [4].

Much PV waste currently is disposed of in landfill. Considering summarization of input and outputs of the 'FRELP' process for the recycling of 1000 kg of silicon PV waste panels following data can be deducted.

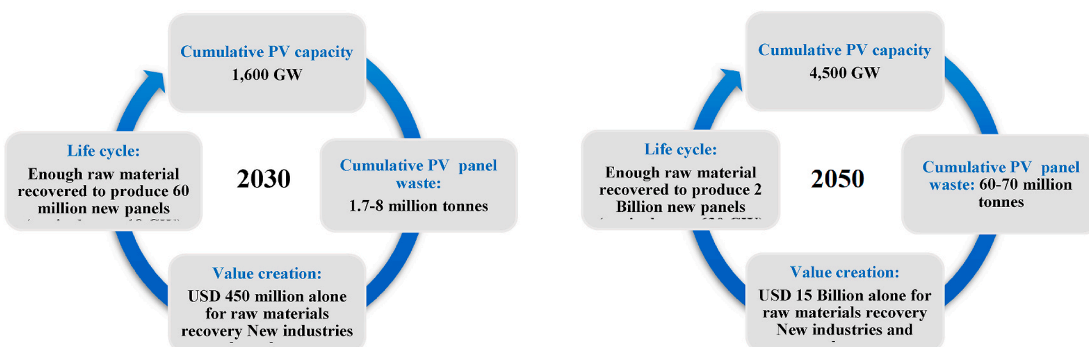

Fig. 2. Potential value creation through PV EOL management [5].

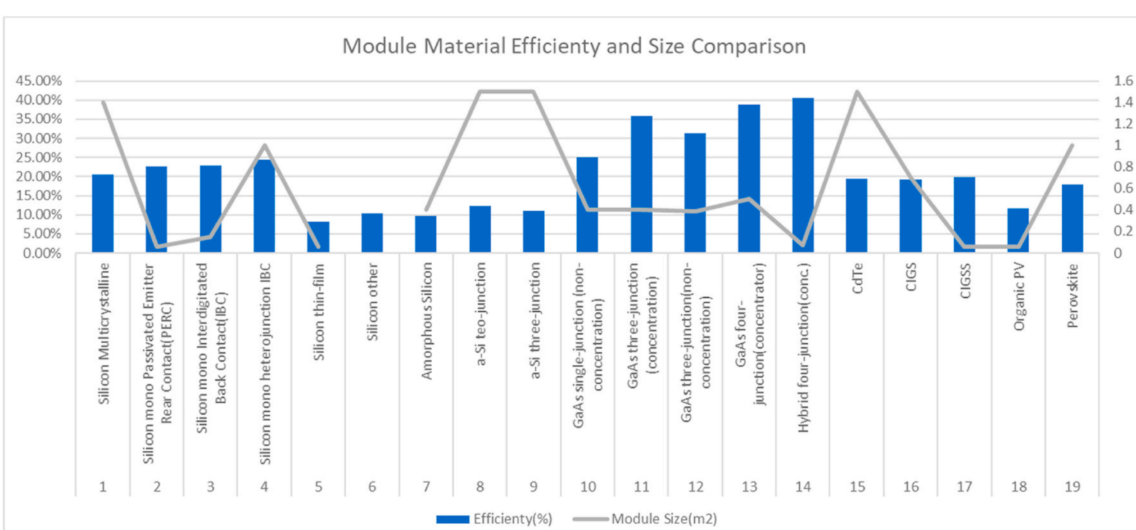

Fig. 3. Module efficiencies and Size (%) [16].

Table 1
Types of solar panels and other innovations in solar panels.

Sr. No.	Module/Panel Type	Material	Pros	Cons
1	Monocrystalline solar panels	Single crystal silicon	1 High durability 2 Higher efficiency 3 Less space required	1 High initial cost 2 Fragile 3 Silicon wastage
2	Polycrystalline solar panels	Fragments of silicon	1 Less cost as compared with mono-Si 2 Silicon waste from mono-Si panels can be used	1 Less efficiency
3	Amorphous silicon solar panels	Various material depending on type	1 Less costly as compared to silicon-based panels	1 Less efficient as compared to silicon-based panels
4	Gallium arsenide		2 Can be used where space is not a constraint	2 Cannot be used where less space is available
5	Copper indium gallium selenide			
6	Cadmium telluride			
7	Concentrator PV technology	silicon, CdTe, CIGS, multi junction	1 Highest efficiency 2 Usage of other accessories increases the cost but improves the functional ability and efficiency	1 . Expensive
8	Hetero-junction technology	Combination of crystalline & a-Si	1 More efficiency than mono-Si 2 More power output 3 Increase in performance	1 Expensive
9	Bifacial solar technology	Silicon solar cells	1 Absorbs light reflected from ground 2 Solar trackers can be used to yield more energy 3 Used for commercial purpose	1 Not suitable for rooftop installation
10	Solar tile/roof technology	Silicon based/ thin film	1 Portable 2 Longer life	1 Appearance of roof 2 Strong roof material (additional cost)
11	Transparent solar panels	Transparent luminescent solar concentrator, comprises of organic salt	1 Low cost 2 Commercial purpose	1 Lowest efficiency
12	Half cut solar cells	Silicon solar cells	1 Improves power output 2 Slight increase in efficiency 3 Pay-back period is less 4 Reduce resistive losses 5 Longer life than complete solar cells	1 Precision task - cost increases 2 Chances of electrical defects increases
13	Dye sensitised solar cells	TiO_2, covered with a molecular dye that absorbs sunlight	1 Low cost 2 Operational in low light	1 Electrolyte has its own chemical constraint, not suitable in every condition. 2 Cannot be used on large scale
14	Perovskite solar cells	hybrid organic-inorganic lead or tin halide-based material e.g.,$MAPbI_3$	1 Improves the efficiency and lowers the cost. 2 Reacts to different wavelengths of light. 3 Light weight	1 Toxic material 2 Cheaper cells have shorter lifespan 3 Presence of moisture affects the overall life of the cell.
15	Bio hybrid solar cell	Combination of organic and inorganic matter	1 Higher conversion rate (solar to electricity) 2 Better efficiency	1 Life span is shortest (few weeks – 9 months)

1. Contaminated glass: 14 kg disposal in landfill
2. Fly ash (hazardous waste): 2 kg disposal in hazardous waste landfill
3. Liquid waste: 306.13 kg disposal in landfill
4. Sludge (hazardous waste): 50.25 kg contains metallic residue, disposal in a special landfill [6].

Hence, the landfill option produces additional costs and also the material inherent values will not be recovered from the existing PV modules. Proper disposal of many compounds is not yet discovered; hence they are landfilled without any treatment, which causes harm to the environment [7].

Hence due to such largescale drawbacks of landfills usage, different recycling methods are produced globally to reduce the environmental effect of EOL and to recover the inherent values of materials from old PV modules. The sustainable growth and development of the PV industry should be subsidized globally by the formation of regulatory frameworks and organizations, which is not the case at the moment. There must be ample policies to have a straightforward path for EOL PV modules when they are completely decommissioned.

Among the different PV panel technologies, crystalline Si modules represent 85–90% of the market (data provided by the IEA). GWP produced by recycling of 1 tonne of Si PV panels is equal to 370 kg CO_2eq/kg [6], saving approximately 800–1200 kg CO_2eq/kg in case of a module 100% manufactured from primary materials. Moreover, PV energy sources generate power with low levels of carbon emissions that cause global warming. In addition, fossil fuel-generated electricity accounts for CO_2 emissions of between 400 and 1000 g CO_2eq/kWh, whereas CO_2 emission from silicon-based solar panels are negligible [8].

Solar PV is one of the most promising renewable energy technologies: it is clean, reliable, flexible, silent and free of cost available [9,10]. One of the key questions for recycling of solar panels is whether recovering materials is better for the environment compared to extracting and using virgin materials.

A study represents significant reduction in EPBT (factor of 1.8 is seen from 100% virgin to 100% recycled scenario) [11].

Several recent studies did suggest that the environmental impacts from recycling are less than using virgin materials but how much less has

Table 2
Average material composition and classification of PV modules per technology [18,23].

METAL INVENTORY		c-Si		a-Si		CdTe		CIGS	
		[Kg/m^2]	[%]	[Kg/m^2]	[%]	[Kg/m^2]	[%]	[Kg/m^2]	[%]
PRECIOUS METALS BASE AND SPECIAL METALS	Silver	8.89E−03	5.77E-02						
	Aluminum	2.54E+00	1.65E+01	3.24E+00	4.16E+01	1.50E−02	9.04E-02	1.51E+00	8.58E+00
	Copper	1.13E−01	7.31E-01	7.00E−02	8.99E-01	5.00E−01	3.01E+00	5.00E−02	2.84E-01
	Nickel	1.63E−04	1.06E-03	–	–	–	–	–	–
	Iron	–	–	5.80E−05	7.43E-04	–	–	–	–
	Titanium	8.01E−07	5.20E-06	–	–	2.30E−08	1.39E-07	–	–
	Tin	9.02E−06	5.86E-05	–	–	2.30E−07	1.39E-06	1.00E−02	5.68E-02
	Zinc	1.20E−06	7.81E-06	2.90E−05	3.72E-04	3.00E−08	1.81E-07	1.00E−02	5.68E-02
	Chromium	–	–	4.40E−05	5.65E-04	3.00E−03	1.81E-02	–	–
	Manganese	–	–	7.30E−05	9.37E-04	–	–	–	–
	Molybdenum	–	–		–	–	–	1.00E−02	5.68E-02
HAZARDOUS METALS	Cadmium	–	–	4.00E−04	5.13E-03	2.00E−02	1.20E-01	3.00E−02	1.71E-01
	Lead	7.20E−04	4.67E-03	–	–	7.00E−04	4.22E-03	–	–
	Selenium	–	–	–	–	–	–	1.00E−02	5.68E-02
CRITICAL SUBSTANCES	Magnesium		5.20E-01		1.31E+00	–	–		2.67E-01
	Gallium	–	–		–	–	–	1.00E−02	5.68E-02
	Indium	–	–	9.00E−04	1.16E-02	–	–	5.00E−03	2.84E-02
	Tellurium	–	–	5.00E−04	6.42E-03	2.00E−02	1.20E-01	–	–
OTHER METALS/METALLOIDS	Silicon	1.22E−01	7.91E-01	2.00E−04	2.57E-03	5.00E−02	3.10E-01	–	–
	Steel	1.47E+00	9.51E+00	3.10E+00	3.98E+01	2.00E−01	1.20E+00	–	–
OTHER MATERIALS	EVA	1.00E+00	6.50E+00	1.24E+00	1.59E+01	6.00E−01	3.61E+00	9.00E−01	5.12E+00
	Glass	1.01E+01	6.54E+01	3.58E−02	4.59E-01	1.52E+01	9.15E+01	1.50E+01	8.53E+01
TOTAL		1.54E+01	1.00E+02	7.82E+00	1.00E+02	1.66E+01	1.00E+02	1.76E+01	1.00E+02

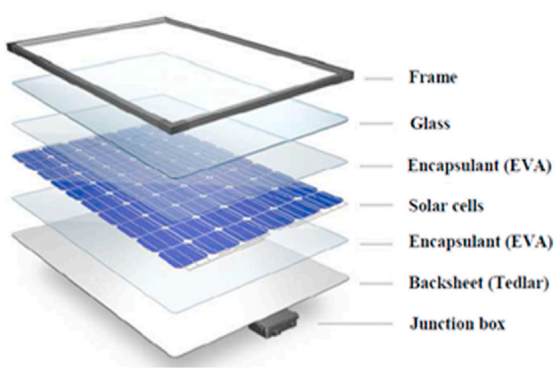

Fig. 4. Structure of the photovoltaic module [21].

been uncertain and one study even found that recycling may lead to higher impacts than using virgin materials [11]. One reason for this uncertainty is that there are different recycling processes and the environmental impacts from each may vary greatly [12].

There are two ways of looking at the expected PV panel waste accumulation for the future: regular and early loss scenarios.

The regular loss scenario assumes the panels operate for their manufacturer guaranteed lifespan, roughly 30 years, with no premature retirement or failures [13,14]. Early loss includes all likely “infant”, “mid-life”, and “wear-out” failure possibilities before the 5 panel’s 30-year lifetime is up [15].

Overall, the vast majority of panels end up making it to their EOL and early loss is only a minor contributor to waste.

Therefore, solar PV panel EOL management is an evolving field that requires further research and development. This review also helps in recommending future directions for public policymakers and researchers & reviewers to get the overall idea of what progress has been achieved in the PV world.

Henceforth the paper is divided into following sections.

1. Introduction
2. Single line diagram
3. Types of solar panels and technologies available
4. PV structure and material characterization
5 Recycling methods
6. Cost of recycling
7 Efficiency comparison: new-existing-recycled
8. Waste composition and generation
9. Environmental impact
10 Conclusion

2. Working and connections in solar PV plant

1. Solar modules are connected in series to form a string. Different strings are connected in parallel to form a solar array.
2. Modules are added in series to increase the voltage level.
3. Individual strings are connected in parallel to form a solar array.
4. Inverter input MPPT channels and string connections to be checked from the data sheet of the inverter.
5. As per the input DC voltage of the inverter modules are connected in series and as per the maximum input power of the inverter total modules are calculated and connected in series.
6. Various inverter powers are combined in the ACDB panel. ACDB panels mainly combine power from all input inverters to provide single source solar power into the grid.
7. Looking from the grid side the same panel will act as an AC distribution panel, distributing the grid supply to individual inverters.
8. Final evacuation ACDB panel is the panel located near the evacuation panel at customer end.
9. Output from ACDBs shall come to main ACDB and output from main ACDB is directly terminated in the existing LT panel/bus coupler with the help of AC power cables.

3. Types of solar panels and other innovations in solar panels

3.1. Components of photovoltaic system

The components of a photovoltaic system can be divided into the PV modules and BOS. PV modules are layers of glass, EVA, metals, PV cells, etc. [17] The BOS includes all the other components, including inverter, transformer, mounting structure, cables, tracking systems, and batteries [18].

3.2. Detailed explanation

Following are the technologies available in the global market on a larger front (see Tables 1,2 and Fig. 4):

1) Silicon based solar panels

- Mono-Si
- Poly-Si

2) Thin-film technology

- a-Si
- GaAs
- CIGS
- CdTe

3) Following evolution has been done in silicon based solar panels & thin film technology:

- Half cut solar cells
- Bifacial solar technology
- HJT
- CPV
- DSC
- Perovskite solar cells
- Bio hybrid solar cells

4) Following are the emerging technologies which are on a smaller scale or under research.

- Solar tiles/Solar roof technology
- Transparent solar panels

1. Mono-Si: Each cell is constructed from a single crystal. Pure silicon is melted and crystallised into ingots, after the formation of ingots in the manufacturing process it is cut in wafer form with a thickness of about 200–300 μm.
2. Poly-Si: They are also called multi-crystalline solar panels, they consist of multiple fragments of Silicon, arranged in an irregular pattern, melted together and forming into blocks and are cut down into wafers and it doesn't have cuts like mono-Si panels. As it doesn't have silicon in its purified form as mono-Si, its efficiency is less.
3. Thin film Technologies: These are 2nd generation solar cells. These are made of different combinations of materials, reducing the cost of overall panels as compared to mono-Si & poly-Si. It has a simpler process than silicon wafers manufacturing.
4. Half cut Solar cells: They are silicon cells which are sliced into half by laser cutter. This method has various benefits over traditional methods. They are available in both mono-Si & poly-Si.
5. Bifacial solar technology: It is dual glass design with a clear back-sheet leading to maximum usage of solar energy. It requires a minimum amount of shaded space and support racks so that maximum advantage can be taken of back faced cells. Back-faced cells try to capture the solar rays reflected from ground which leads to increase in efficiency and power output. They are available in both mono-Si & poly-Si.
6. HJT: It is a combination of the best qualities of crystalline Si with those of a-Si to produce higher energy as it has lower temperature coefficient than other modules. The crystalline silicon brings the increased efficiency and a-Si brings the light absorption ability thus leading to overall increase in efficiency.
7. CPV: This method is the most efficient method till date it uses concentrator PV cells to produce electricity. Compared to other existing technology it consists of curved mirror surfaces, lenses and additional components which increases the cost and efficiency.
8. DSC: These solar cells use molecular dyes to absorb the solar spectrum precisely. The dye molecules are bound to TiO_2 and the porous network is then infiltrated by either an electrolyte or a conducting polymer. The exciton generated in the dye is then separated as the electron is very rapidly injected in the oxide. The dye cation is revived by either a redox shuttle in the electrolyte or a hole conducting polymer. The theory of hybrid organic–inorganic solar cells is found on the sensitization of porous semiconducting metal oxide films with organic or metal-organic dyes. DSC's technology benefits from fabrication through abundant, nontoxic, and cheap materials, as well as tunable colour depending upon the dye employed and relatively high-power conversion efficiencies (up to 14.0% [19] for liquid and 7.5% [20] for solid state devices at the laboratory scale)
9. Perovskite solar cells: It is created from hybrid organic-inorganic lead or tin halide-based material. These materials are economical and easy to manufacture. It has a broader absorption spectrum which allows it to trap photons of different wavelengths hence increasing overall efficiency. They are lightweight and flexible.

4. PV structure and material characterization

The structural formation of the module is as follows (see Fig. 4): On the top of the PV module tempered glass is placed. The glass can withstand large hails and is highly shock resistant. EVA film is applied between glass and PV cells. Again, the EVA film is deposited between PV cells and back sheet made of polyvinyl fluoride (Tedlar). Air is removed from the space within and EVA is heated above the melting point which eventually acts as a sealing compound. The modules are framed and sealed with silicon sealant into aluminum contour and provided with a junction box with output contacts [21].

Material characteristics play an important role from manufacturing, cost, efficiency, and environmental aspects. Glass is commonly used in thin film PV panels as thin-film PV modules because it is a solid, inexpensive substrate on which thin layers of semiconductor material are applied. An exception to this is a-Si which uses aluminum (42%) and steel (40%) as back sheet. The encapsulant material EVA (Ethyl Vinyl Acetate) accounts for 4–16% of the material composition of the PV panels. C–Si contains 10% steel whilst CdTe uses only 1%. Silicon represents 0.8% of material composition in c-Si technology because it is used for the solar cells, and although a-Si uses Si as well, it is used in a thin layer that only represents 0.0026%. Aluminum is another metal broadly used in PV panels, because the frame of modules is made of aluminum alloys, accounting for 9–42% of mass. The aluminum alloy considered is $AlMg_3$, so magnesium is present in the three panels that use an aluminum frame. Thin film CdTe solar modules have no frame. Copper is used for interconnectors accounting for 0.3–3%.

1) Silicon based solar panels:

- Mono-Si:

It is single crystal silicon with no grain boundaries. It is manufactured using Czochralski method (It is a method of crystal growth for obtaining single crystal of semiconductor).

- Poly-Si:

It is made of several mono-Si fragments, it has several grain boundaries as it is not made from pure silicon, which acts as a barrier for excitation of electrons. Manufacturing process is simpler and cheaper as compared to mono-Si [22].

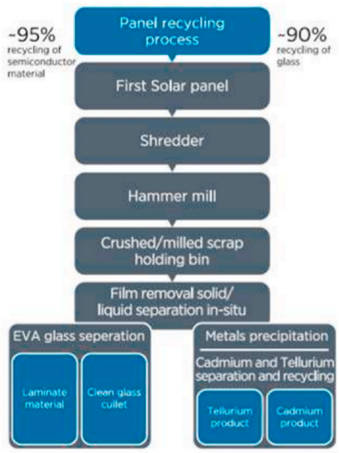

Fig. 5. Examples of the process of compound (CdTe) module recycling [13].

2) Thin film based solar panels:

- a-Si:

These technologies are competitors to crystalline silicon due to cost & efficiency. There are many other factors which require development such as poor minority-carrier lifetime, degradation of cell performance due to illumination, difficulty in materials dopant and poor-quality alloys [22].

- Various thin film technologies:

Materials such as CdTe, CIGS, GaAs are considered as an alternative to silicon cells. Among all, CIGS is useful due to the remarkably high efficiency for poly-Si thin films, at 18.8% in the laboratory, because of a band gap of 1.1–1.2 eV there are other problems related to cost.

CdTe is also considered due its high optical absorption and variety of deposition techniques (e.g., close-spaced vapor transport, electrodeposition, and screen printing) producing a variety of junction structures. The major problem with CdTe is that Cd is a toxic material.

5. Recycling methods

The most common methods for recycling c-Si as well as CdTe modules are based on mechanical, thermal and chemical processes (see Fig. 6). Although thin-film solar cells use far less material than c-Si cells, there are concerns about the availability and toxicity of materials such as tellurium, indium, and cadmium, for example. Various techniques of recycling can be seen in Figs. 7 and 8. Furthermore, the production processes also generate greenhouse gases emissions during some reactor-cleaning operations [24].

And the process for a CdTe module operated by First Solar, shown in Figs. 3, 5 and 6, can gain a recovery rate of nearly 90% for glass and approximately 95% for semiconductor materials by mass. Other than CdTe, the recycling of thin-film PV modules is still in its early stages. But, as waste volumes and the corresponding amount of waste treatment knowledge increase, the process will be improved [13,14]. Also, CdTe out of all the other technologies mentioned is the second most deployed (15% globally), and not phasing out (like a-Si), or non-commercial (like most of the other examples).

5.1. Recovery

5.1.1. Al frame and glass recovery from solar panels

Different layers of solar panels are separated by thermal treatment. The heating condition is important to avoid breaking silicon wafers. This is because the wafers have a significant impact on the total price. The recycling of unbroken silicon wafers can reduce the manufacturing cost by decreasing the energy consumption in silicon purification and wafer manufacture.

Heating was performed in steps for separation of different components. First the solar panels were heated to 250 °C in order to detach the Al frames (Fig. 4). Secondly, the panels were heated to 480 °C at a rate of 15 °C/min to separate the different layers of EVA. After the thermal

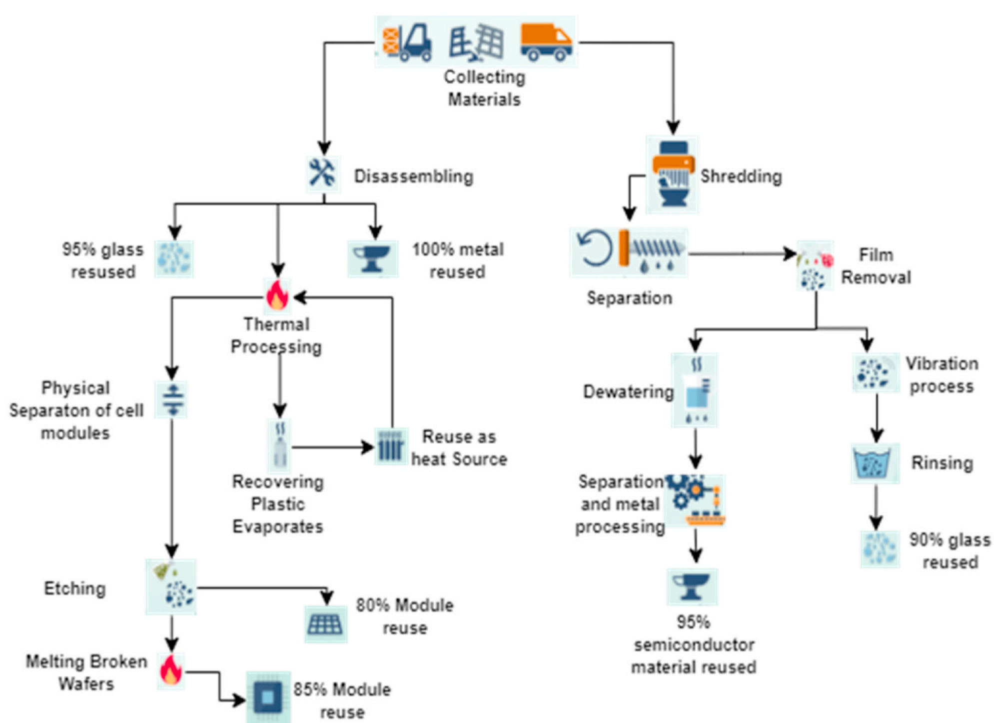

Fig. 6. Recycling process.

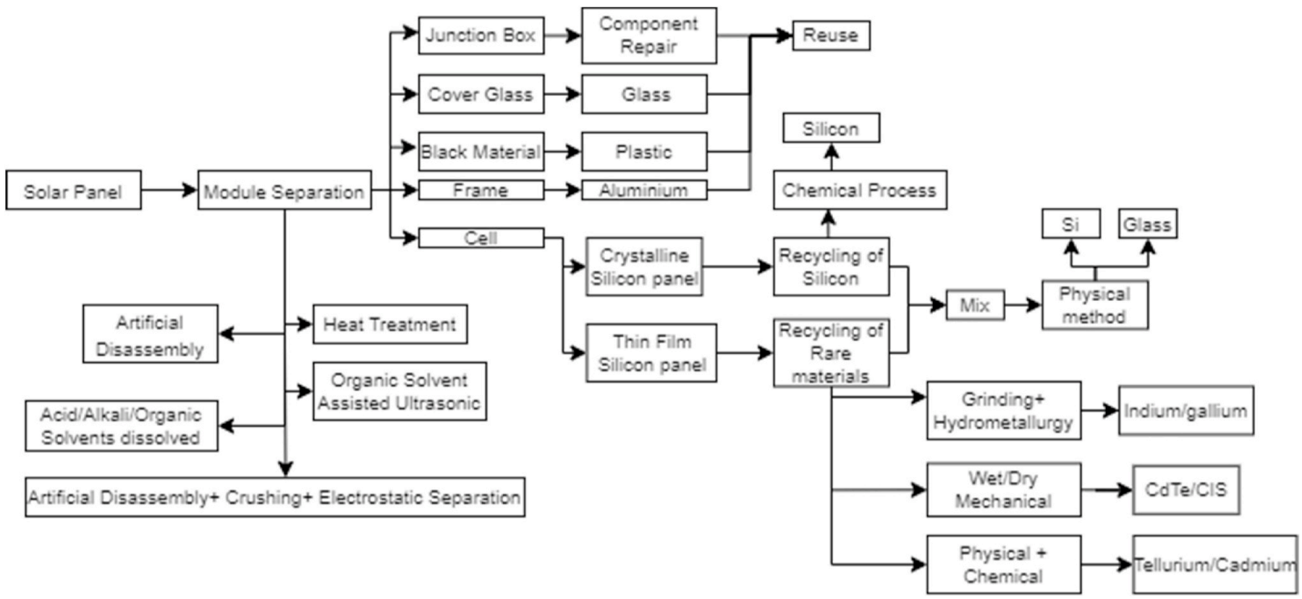

Fig. 7. Recycling techniques for various types of solar panels.

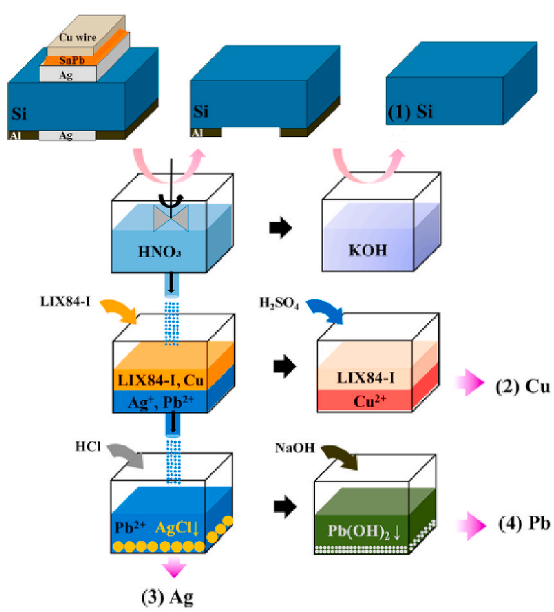

Fig. 8. Process flow for raw-metal recovery from solar cells.

2) Al recovery consists of two steps:

process, glass without cracks was recovered and then the remaining solar cells and Cu wires were collected [24].

5.1.2. Process for dissolving metals from the solar cells and Cu wires

The leaching solution contained Ag, Al, Cu, and Pb after the leaching process. To ensure efficient recovery, Si, Cu, Ag, Pb, and Al were sequentially extracted.

1) First, a simple filtration process was implemented to obtain Si. The wafers contain impurities such as SiNx and Al electrodes. To recover the wafers, removing the SiNx and Al electrodes was necessary. There are two steps in removal process:

1. Immersion of Si wafers in 90% H_3PO_4 solution at 160 °C for 60 min to remove SiNx
2. Immersion of the Si wafers in 45% KOH solution at 80 °C for 10 min [25,26].

1. Recovery of Al frame via a thermal process.
2. Recovery of Al in the form of $Al(OH)_3$ in KOH solution using simple filtration, followed by heating at 1200 °C for 3hr. This process

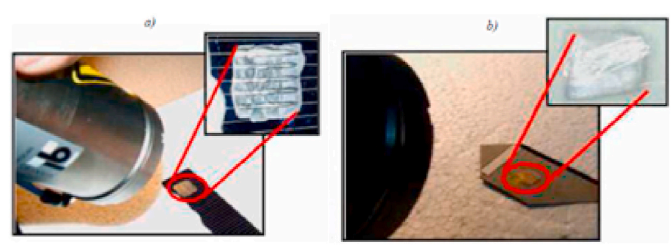

Fig. 9. PV cell surface cleaning with a neodym laser-a) front side, b) rear side of PV cell.

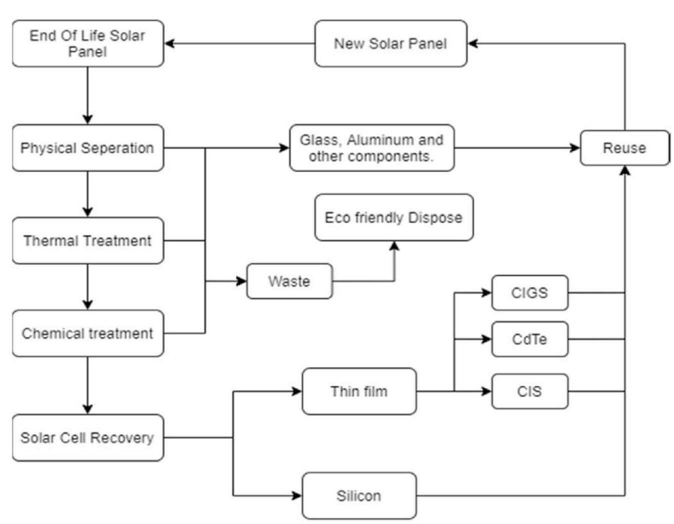

Fig. 10. Different types of solar PV recycling processes [28,43].

allowed easy recovery of Al_2O_3 [27]. Recovery rates for Si and Al were 80% and 94%, respectively.

3) Cu recovery involves three steps:

1. 20% LIX84-I was used to extract Cu from the leaching solution. Cu ions were separated from the HNO_3 solution containing Ag and Pb (Fig. 9) (see Fig. 10).
2. H_2SO_4 concentration of 150 g/L to the LIX84-I fraction to strip the Cu. This step causes Cu to move from the LIX84-I layer to the H_2SO_4 solution by forming $CuSO_4$.
3. A 24hr electrowinning method was applied to recover Cu metal, using 200L of H_2SO_4 solution containing 50 g/L of Cu at 50 °C. A titanium plate coated with IrO_2 and a Cu plate were used as the anode and cathode, respectively.

4) Ag recovery consisted of five steps:

1. 5 M HCl solution was added to the HNO_3 leaching solution containing Ag and Pb to precipitate AgCl, which was then simply filtered.
2. AgCl precipitates to a 5 M NaOH solution at room temperature to obtain Ag_2O.
3. $N_2H_4 \cdot H_2O$ solution in distilled water and ethanol (2:1 vol ratio) to reduce Ag_2O.
4. Ag powder at 1100 °C for 2hr to obtain Ag metal.
5. To obtain high purity Ag (approx. 99.99%), an electrolytic refining process was used. Refining was performed in 0.06 M HNO_3 solution containing 0.3 M $AgNO_3$ for 24 h at four different solution temperatures (25, 30, 40, and 50 °C).

5) Pb recovery consisted of three steps:

1. 5 M NaOH solution was added to a leaching solution containing Pb^{2+} ions at room temperature. Pb^{2+} reacted with OH- in the solution, forming $Pb(OH)_2$ precipitate, which was removed by filtration.
2. $Pb(OH)_2$ was heated at 500 °C for 1 h to obtain PbO.
3. 5 M Na_2S solution is added to the HNO_3 solution to remove the remaining Pb in solution. This step led to precipitation of PbS, which was removed by filtration [24].

5.2. Separation

5.2.1. Separation and cleaning

5.2.1.1. PV recycling process consists of two main phases.

1. Separating of PV cells: Using chemical or thermal procedures, the cells are separated in the recycling process. EVA, glass, Tedlar, aluminium frame, steel, copper and plastics are removed and separated from each other in this step

2. Cleaning the cell surface: During this phase, separated cells from PV modules are cleaned chemically or by laser techniques [25].

Laser surface cleaning method has been developed to obtain clean silicon substrates. Laser pre-treatment of PV modules before the separation of its components is a very successful technique used especially in some PV module recycling companies in Germany. The laser method was compared with the chemical etching of the surface through the experiment with neodymium laser.

It has been found that the chemical treatment from the above procedure is far more advantageous than the laser method. The laser method is expensive, and the process is not very efficient. The time to remove the layers using the laser method is about 1 min/cm^2. It is possible to clean the whole surface of the cell by chemical treatment during this time [21].

Thermic processes are a simple and fast approach to separate components. It's economically feasible [32].

5.2.2. Module separation and extraction of material

5.2.2.1. Physical separation: separation by mechanical process of broken panels. EVA removal: Author prescribed the recovery of silicon panels using an organic solvent method. Different tests using multiple types of organic solvents to dissolve the EVA film were carried out, it was found that trichloroethylene could melt cross-linked EVA samples kept at 80 °C. Extinguishing the EVA film by using high temperature pyrolysis, or dissolving the EVA by using acid, alkali and organic solvents, have been effective techniques [33]. Author used an organic solvent-assisted ultrasonic method to improve the dissolution rate of the EVA, and utilized trichloroethylene, o-dichlorobenzene, benzene, toluene, and other organic solvents to dissolve the EVA film from solar panels. The results showed that at the temperature of 70 °C and 450W ultrasonic power, the EVA film could be completely dissolved in 3 mol/L of toluene after 1 h. This procedure significantly shortens the dissolution time of EVA in organic solvents, but could also lead to an organic liquid waste problem [34].

A Japanese company developed a hot-knife method in which a steel blade heated to about 300 °C slices through the EVA to separate the cells from the glass [35]. This method is particularly suitable for mobile applications, but at 300 °C, the EVA does not decompose so there is residual EVA on the cells and glass necessitating pyrolysis after the hot-knife step.

Different materials removal process: The Al electrodes on the backs of the panels are separated with a sodium hydroxide solution. Potassium nitrate solution is used to recover silver positive electrodes. Hydrometallurgy process is used to separate gallium and indium materials from solar panels. Method was developed by Vital Materials Limited Company [36]. Author also studied the recycling of thin-film solar panels, such as recycling CIGS and CdTe by wet mechanical treatment: (using grinding and flotation for example), or by dry mechanical processing methods such as vacuum blasting [37,38].

5.2.3. Pyrolysis separation

Pyrolysis is a feasible method to cleanly and gently separate Si cells from the glass pane [39–41] because it avoids generation of toxic HF which is released when EVA layers, Si cells, and back sheet are still attached to the glass. Recently, a collaboration between TG Companies, Arizona State University, and Canadian Solar demonstrated successful extraction of intact cells from glass by pyrolysis.

The difficulty in separating the module's components was mainly owing to the adhesive material that bonded the glass and semiconductor together. Even when the glass layer was removed mechanically, the adhesive material remained glued to the semiconductor, making its recovery difficult. Thus, the idea of the pyrolysis approach is to remove the adhesive material beforehand, and to separate the other materials afterwards. The analysis occurred in a nitrogen atmosphere [32].

5.2.4. Physical separation

In this process, panels are dismantled by removing the surrounded Al frame, as well as the junction-boxes and embedded cables. Panel, junction-box and cables are shredded and crushed to inspect the toxicity of individual parts and total toxicity of the module for disposal [8].

5.3. Recycling process

As a case study.

Table 3
Previous Research to recover raw materials from solar panels [24].

Target	Treatment Method	Ref.
Glass	Immersion in toluene	[28]
	Treatment @650 °C	[29]
	Crushing the solar panel	
	Thermal treatment	[29]
Silicon	H_2O + 48% + 70% HNO_3 +97% H_2SO_4 + 99% CH_3COOH to remove ARC and p-n junction	[28]
	40% HNO_3 @ 40 °C to remove Ag	[29]
	30% KOH @80 °C to remove Al	
	65% HNO_3 + 40% HF (40%) + 99.5% CH_3COOH (99.5%) + Br_2 to remove ARC and p-n junction	
	60% HNO_3 @25 °C remove Ag	
	Mechanical method to remove ARC and p-n junction	[30]
	45% KOH @ 80 °C to remove Al	
	90% H_3PO_4 @ 160 °C to remove ARC	[31]
	49% HF+60% HNO_3 remove Ag and p-n junction	

Table 4
Parameters of Solartec SMP 1–180 PV modules.

Length (mm)	162
Width (mm)	134
Thickness(mm)	8
Weight(Kg)	0.32
Terminal(mm^2)	2*0.15
Front glass (mm)	3
Solar cell (mm)	16 pieces, Si (14,6*51,2)
Solar cells encapsulation	EVA
Rear side	Tedlar
Frame	Aluminium

5.3.1. Thermal recycling of PV modules [21]

A SOLARTEC SMP 6–180 mini module was used in the comparison experiment between thermal and chemical recycling methods (see Table 3). See the specification in Table 4 and weight distribution in Table 5

TG is an analysis that quantitatively monitors the weight change (gain, loss) of the measured sample [44].

Thermogravity indicated instantaneous weight of the sample depending on temperature and time. The decomposition temperatures of the separated plastic materials and polymers was determined as 445.44 °C, and also heating rate and maximum temperature of 479.22 °C at which the PV module was heated in a special furnace (see Fig. 11).

The PV module was placed in a vessel and heated to a temperature above 420 °C. The temperature increase was around 20 °C/min. The photovoltaic module was heated in the furnace for 25 min. The plastic materials evaporated, and the PV cells were separated from the glass, see Figs. 12 and 13.

The length of the process was significantly lower in comparison with the chemical treatment.

The disadvantage of thermal recycling is the formation of emission gases during thermal evaporation of the EVA copolymer. The recycling process is energy-consuming, but up to 85% of the recycled cells can be reused and reduce manufacturing energy consumption of the new PV

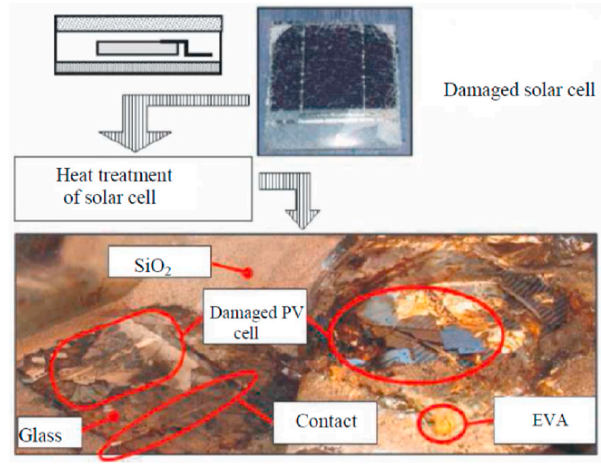

Fig. 11. Thermal recycling of the encapsulated Solartec PV module.[21]

modules by up to 70%. This method due to its simplicity and high efficiency can be used for commercial recycling of PV modules with better results than chemical methods [21].

5.3.2. Mechanical recycling

PV modules are first crushed in the crusher and then shredded to desired sizes of approximately 4–5 mm. The PV module lamination gets damaged in this way. The glass is disassociated from a larger section of laminate film due to the size of the milling cutter.

Remaining parts of the laminate film are separated from the glass fragments in the vibrating network. In terms of output quality, combinations of mechanical and thermal processes allow better recycling of modules and makes it possible to get more valuable materials with high yield and good quality. Pure glass shards are sent to the glass industry for recycling.

5.3.2.1. Mechanical recycling method of damaged PV modules. Two damaged monocrystalline PV modules ASEC-230G6S were selected for recycling.

In the first step, the modules were mechanically processed and prepared for recycling. The aluminium frames, which were silicon-secured

Fig. 12. Heat treatment of PV modules.

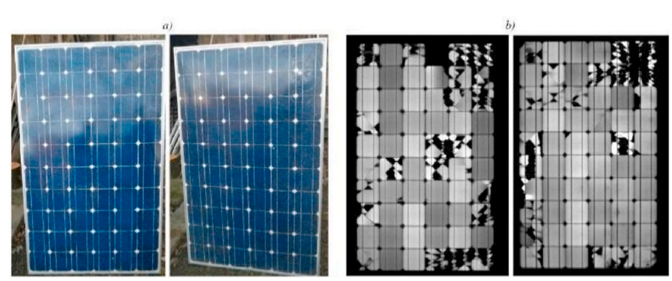

Fig. 13. a) Damaged PV module number 1(on the left) and number 2 (on the right); b) Electroluminescence measurement of module number 1(on the left) and number 2 (on the right).

Table 5
Weight distribution of individual PV modules parts.[44]

	Weight [Kg]	Percentage share [%]
Total weight of the modules	38	100
Aluminium frame	7	18.42
The largest pieces of fraction >11.2 mm	5.3	13.95
The medium pieces of fraction >5.6 mm	14.2	37.37
The smallest pieces of fraction >1 mm	11	28.95
Connection boxes	0.5	1.31

Fig. 14. a) Removal aluminium frames and junction boxes; b) PV modules cutting into two halves.

and screwed together, were removed from the modules, (see Figs. 14 and 15).

5.3.3. *Advanced recycling technologies*

In the second step, PV modules were rolled and cut into two halves on hydraulic shears for a better crushing process in a chain crusher, see Fig. 16 b). The cut modules were placed on a conveyor that moved them to a chain crusher. The chain crusher crushed them again into different pieces and fractions, see Fig. 16.

The resulting material was divided into individual fractions by size through a mechanical separator and sieves.

The next step in the recycling process was chemical etching to obtain precious metals. Crushed materials were already free of glass. The whole process took place in a stainless reactor with nitric acid.

5.3.3.1. *Benefits of mechanical recycling.*

1. Recycled shards are used to replace the original material in glass. The basic composite for glass production consists of materials containing carbonates such as limestone, dolomite, soda/sodium carbonate.
2. Reducing CO_2 emissions in the melting process. Resulting CO_2 emission is about 30% of total CO_2 emission in relation to carbon released from primary materials. It is therefore advantageous to reduce these emissions by using glass shards instead of primary materials.
3. Reduction of energy in the melting process. Lower melting temperature of glass as compared to the base material leads to lower energy consumption in the glass melting process. The potential for reducing the energy of glass is in the range of about 3%–10% of glass shards. This is considered to be valuable for reducing fuel consumption and associated emissions [21].

5.3.4. *What to recover from Si modules?*

With the revenue far below the cost for Si module recycling, it is worthwhile to rethink about what to recover from waste Si modules in an attempt to increase the revenue and offset the cost. There are three potential recycling scenarios for waste Si modules [46].

1. Refurbish and reuse waste modules;
2. Extract and reuse components from waste modules;
3. Extract and reuse materials from waste modules.

Each scenario requires a different recycling process sequence with a different cost and revenue associated with it. This section analyses these different recycling scenarios.

5.3.4.1. Reuse of waste modules. Many decommissioned modules are still functioning but at lower efficiencies, typically at 80% of the original efficiencies as guaranteed by the manufacturers. They can be in principle refurbished and reused as a lower-quality product to secondary markets at maybe 50% of the price for new modules. Reuse of decommissioned modules is the first option for recyclers as it requires the fewest processing steps (Fig. 17).

Fig. 15. a) Detail of the crusher; b) Shredded PV modules; c) Crushed.[21]

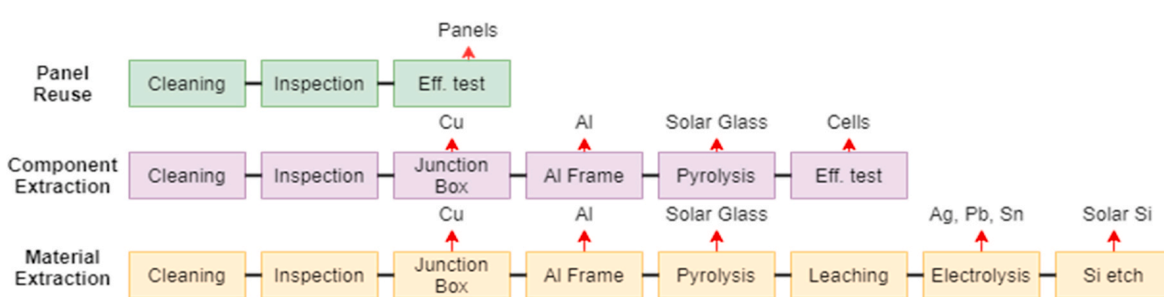

Fig. 16. Three potential recycling scenarios for Si modules recycling [47].

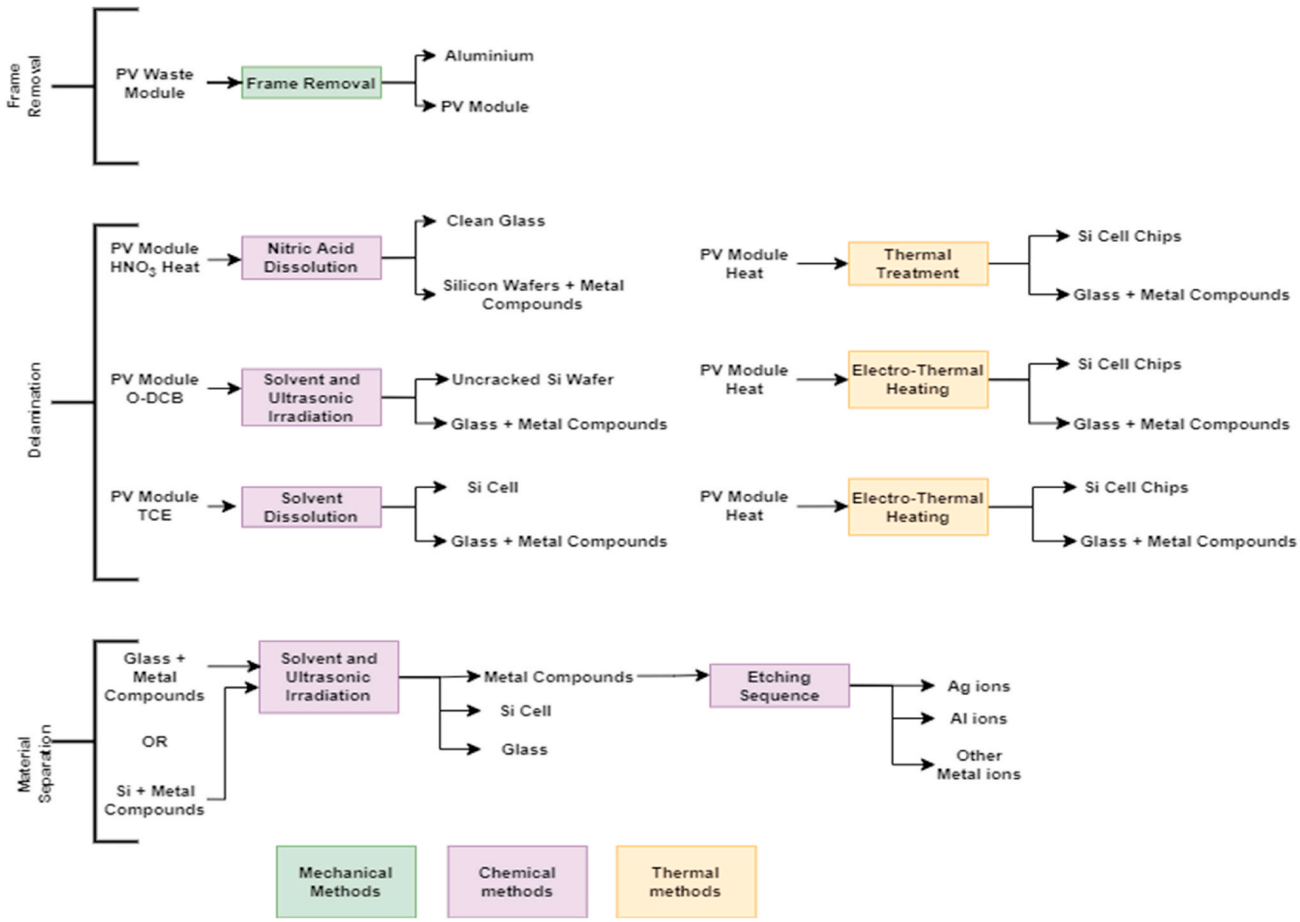

Fig. 17. Delamination and material separation methods for c-Si [12].

1. Cleaning of the modules to remove dust and other deposits on the modules;
2. Visual inspection for damage such as broken glass, punctured backsheet, bubbles in backsheet, burned out wiring, and hotspot;
3. Efficiency test to recertify the modules.

5.3.4.2. Component extraction from waste modules. If modules come in with damage or low efficiency, they cannot be reused. However, some of the components in those modules may be extracted for reuse in remanufactured modules if their performance is comparable with newly produced components. These are the inorganic components of the modules, namely.

1. The glass pane if it is extracted intact and clean;
2. The Si cells if they are extracted intact with good efficiency and solderability.

Inorganic components suffer less degradation than organic components and typically maintain their good performance far longer than the modules they are in. The Al frame and plastic case of the junction box are forcefully removed from the module, so they are damaged during the removal and cannot be reused. The EVA encapsulant, silicon adhesives, and backsheet cannot easily be removed and reused because they have been adhered or cross-linked during the original application process. To extract components for reuse, the EVA layers and backsheet must be removed gently and cleanly in order to have the glass pane and Si cells recovered clean and intact. Component extraction requires more processing steps as compared with module reuse (Fig. 17).

1. Cleaning of the modules;
2. Visual inspection for damaged modules;
3. Removal of junction box from the modules;
4. Extraction of Cu wiring from the junction box;
5. Removal of Al frame from the modules;
6. Separation of Si cells from the glass pane and polymers;
7. Efficiency test to sort the recovered cells.

5.3.4.3. Material extraction from waste modules. If none of the components in a waste module can be reused due to damage or poor performance, our last option is to extract the materials for reuse.

The processing steps for material extraction include the following (Fig. 17).

1. Cleaning of the modules;
2. Visual inspection for damaged modules;
3. Removal of junction box from the modules;
4. Extraction of Cu wiring from the junction box;
5. Removal of Al frame from the modules;
6. Separation of Si cells from the glass and polymers;
7. Dissolution of metals from the cells;
8. Extraction of metals from the leachate;
9. Removal of SiNx,

It is noted that material extraction requires chemical methods, as physical methods are incapable of extracting low-concentration materials from Si modules such as Ag, Pb, and Sn. Chemical methods typically have higher costs than physical methods and generate chemical wastes.

Another important question in material extraction is what quality of Si is to be recovered: ferro-Si, metallurgical-grade Si, or solar-grade Si They have different purity levels. Purer materials generate higher

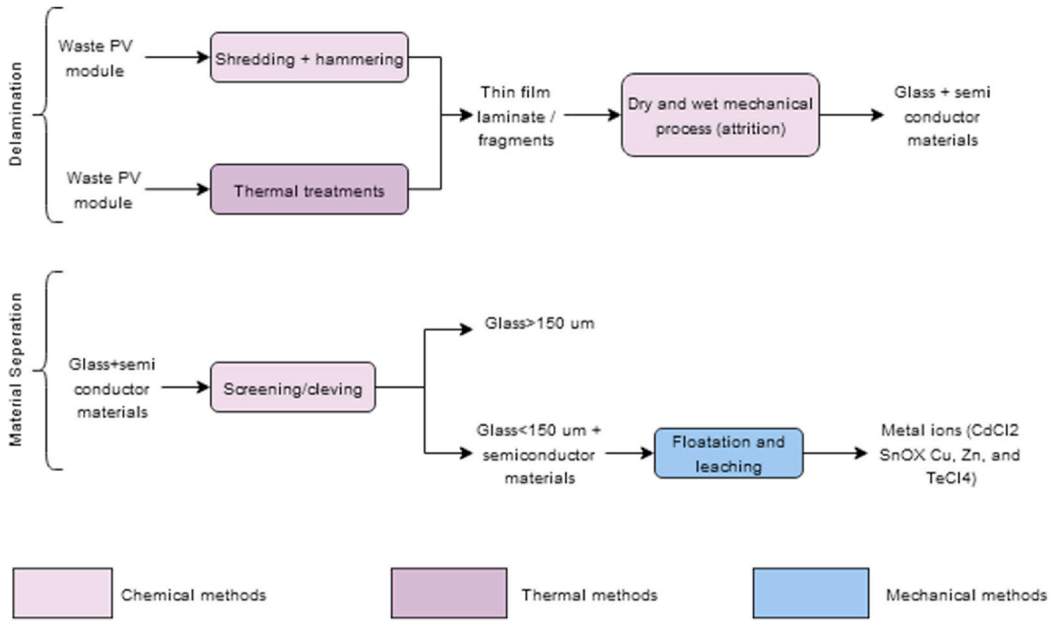

Fig. 18. Delamination and material separation methods for CdTe PV panels. Material inputs for each method are shown in Table 1 [12].

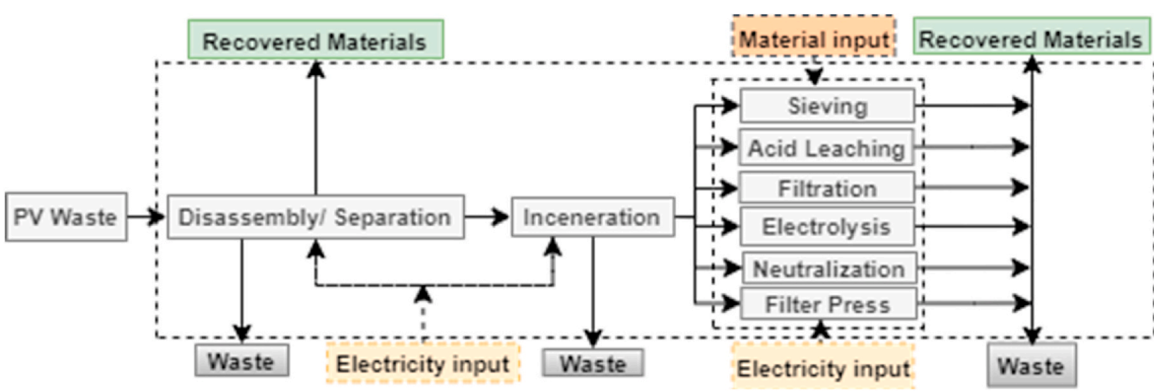

Fig. 19. Simplified PV recycling process modelled from Latunussa et al., 2016 [6].

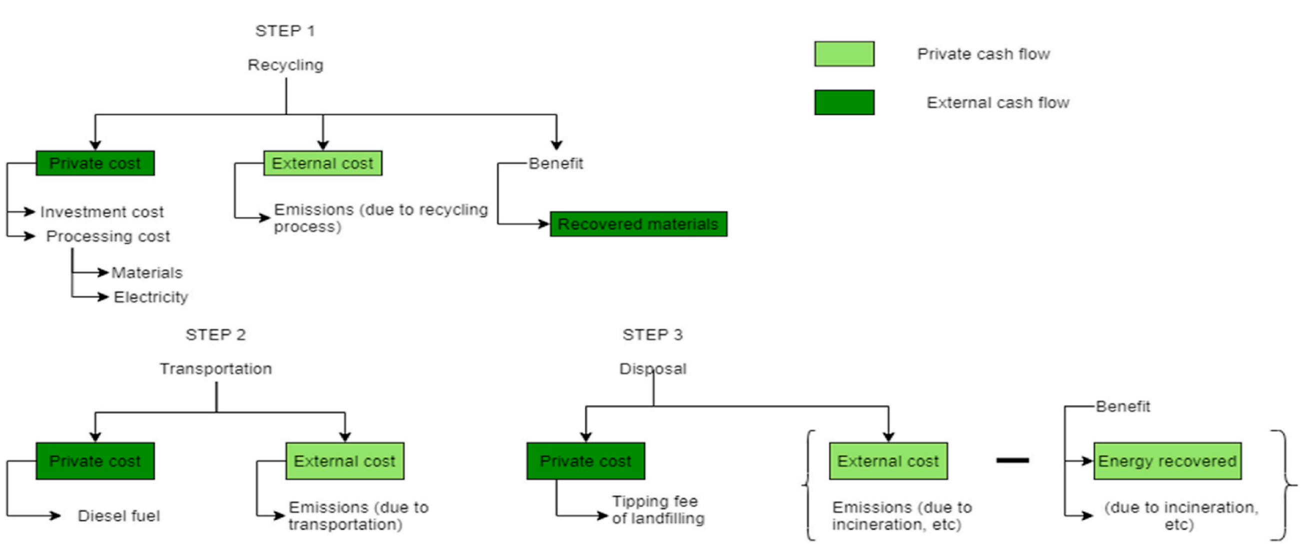

Fig. 20. Our framework in analysing the cost of FRELP recycling method [59].

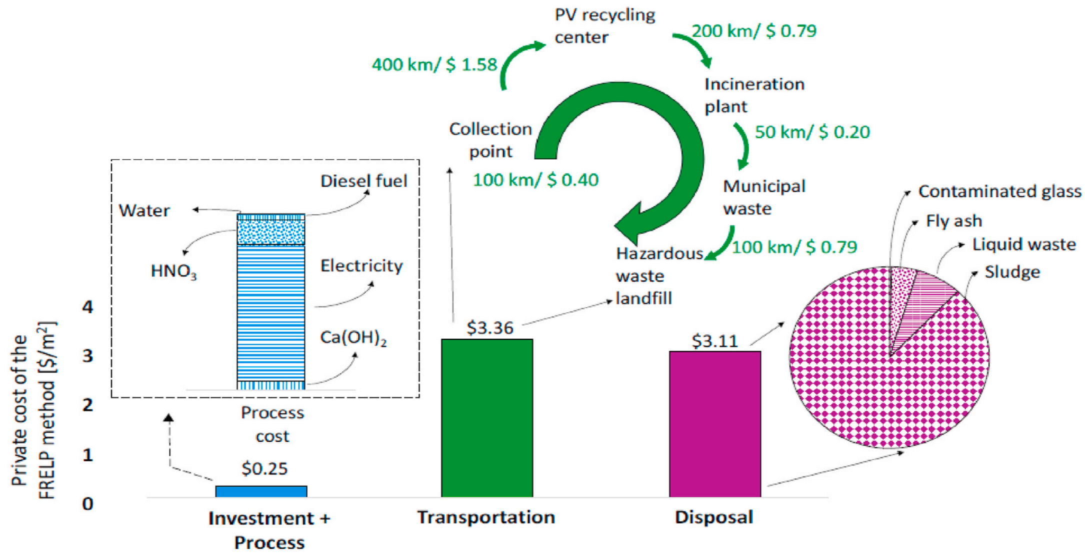

Fig. 21. The end of life (EOL) management (private) cost of EOL of 1 m^2 of c-Si PV [59].

values, but they also require more processing steps. Step 9 in the process

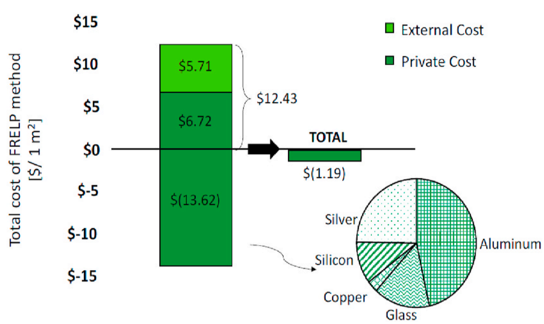

Fig. 22. Total cost breakdown of FRELP project method [59].

sequence above determines whether the recovered Si is metallurgical-grade Si or solar-grade Si.

Due to any reason if extracted Si cells cannot be reused then it is sold as a lower quality of Si hence leading to cost reduction [47].

5.4. PV recycling techniques as per types: CDTE, C–SI

5.4.1. c-Si recycling techniques

5.4.1.1. Method 1. In the recycling of c-Si PV panels there is a frame which needs to be removed before the sandwich layer-like structure is dismantled. The next step is the removal of the EVA layer to separate the glass from the Si cell (delamination). The delamination methods are split into chemical and thermal. After delamination, the glass components, the c-Si cell and metal compounds proceed to the material separation stage. There is only one method of material separation for c-Si and that is chemical etching. However, the scope of this method covers only the delamination and material separation stages which recover over 90% of the PV materials thus material extraction was not included in the final step [12].

5.4.1.2. Method 2. Method of dismantling solar panels and component separation based on physical and chemical properties, structure, and materials. By analysing pros and cons of three methods for solar-panel disposal (artificial disassembly, use of an organic solvent, and heat treatment), it was found that heat treatment process as the prime solution.

Crystal silicon processing process consists of three steps, they are as follows.

1. Sodium hydroxide solution is used to remove AL electrodes from backside of panels

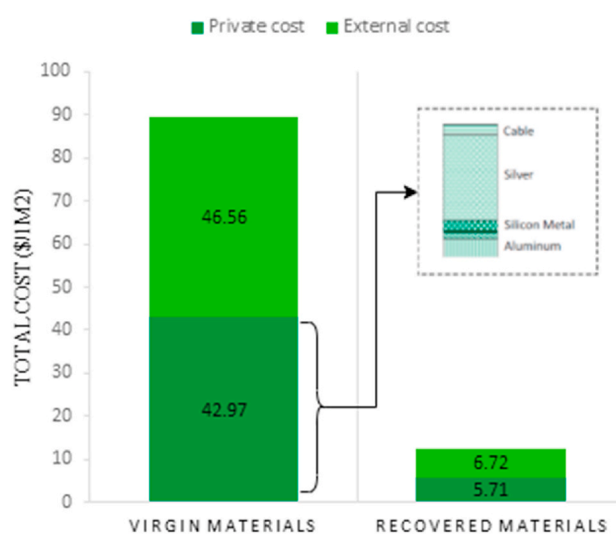

Fig. 23. Virgin material vs Recovered material total cost.

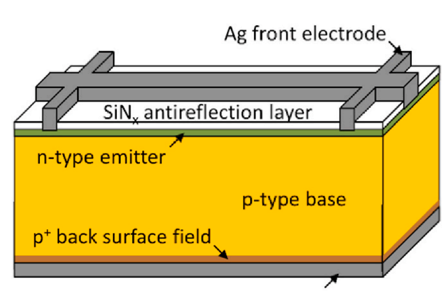

Fig. 24. Schematic structure of today's most common commercial Si cell, the AI BSF cell [Colour figure can be viewed at wileyonlinelibrary.com].

Table 6
PV module waste recycling technologies [7].

Technology	Advantages	Disadvantages
Czochralski mono c-Si process [21]	1. Results in high efficiency mono-crystalline cell	1. Recovery of c-Si mono 2 Lowering the boron concentration to increase cell performance
Hydrometallurgy: oxidation, evaporation, reduction by inorganic reducing agents [36]	1. Recovery of high pure selenium which can be used directly in new solar cells	–
Hydrometallurgy: dissolution, filtration, liquid–liquid extraction, stripping, precipitation electroplating [36]	1. CIS mixed waste recycling 2. Application of normal hydrometallurgical and chemical processes 3. Recovers pure indium	1. Further refining of the processes needed
Organic solvent dissolution [37]	1. The EVA is easy to access 2. Minimum damage to cells 3. Receiving of glass	1. Delamination period is calculated by area 2. Noxious pollution and waste
Organic solvent and ultrasonic irradiation [32,33]	1. More effective than dissolving solvent 2. Easy EVA access	1. Expensive equipment 2. Harmful emissions and wastes
Electro-thermal heating [7]	1. Easy glass removal	1. Time taking process
Pyrolysis (conveyor belt furnace and fluidized bed reactor) [31, 37–39,43]	1. Separate 80% of wafers, and nearly 100% of glass sheets 2. Cost-effective method for industrial recycling	1. Texturization marginally worse (damage to cell surface)
Solvent (nitric acid) dissolution [32,42]	1. Full removal of EVA and metal wafer coating 2. The recovery of intact cells is possible	1. The inorganic acid can cause cell defects 2. Produces polluting emissions and waste
Physical disintegration [27,40]	1. Able to handle waste	1. Other separation processes needed for complete elimination of EVA 2. Dusts which contain heavy metals 3. Solar cell breakage 4. Corrosion of equipment
Dry and wet mechanical process [36,37,47–49]	1. No chemical processes 2. Made readily available equipment 3. Low energy demands	1. Dissolved solids not removed
Thermal treatment (two steps heating) [16,20, 23,24,46]	1. To complete elimination of EVA 2. Possible recuperation of intact cells 3. Measurably viable cycle	1. Toxic emissions 2. High energy demands 3. Cell defects and high-temperature degradation
Chemical etching [12,20, 25]	1. To recover products of high purity 2. Process is quick and efficient	1. Chemicals are used
Component repair [7]	1. Can increase the output power of old solar panels	1. Can be used only if the external junction box outer layer are aging
Module separation [32–37]	1. Mechanical pressure is critical to suppress the swelling of the EVA. The silicon panel was recovered successfully with no damage.	1. Organic liquid waste produced
Recycling of rare metals [7]	1. Recycling of indium and gallium	1. High price of chemicals

Table 7
Revenue from Si of different qualities as of October 30, 2019.[47]

Si Quality	Purity (%)	Weight (kg)	Price ($/kg)	Value ($/Module)
Ferro-Si	75	0.68	0.45	0.31
Metallurgical grade Si	99	0.62	1.5	0.93
Solar grade Si	99.9999	0.56	7.58	4.24
Second grade Si	99.9999	0.56	5.52	3.09

Table 8
Major contributing material percentage in silicon and thin film PV panels.

	Glass	Plastic	Al	Silicon	Metals
Silicon Based	76%	10%	8%	5%	1%
Thin Film	89%	4%	6%	–	1%

2. Potassium nitrate solution is used to recover silver positive electrode grid line
3. HF solution is used to remove any anti-reflectors on the surface of the polysilicon, to recover and recycle high-purity polysilicon.

Yingli New Energy Resources Co., Ltd. of China studied a physical method for recycling solar-panel components. Removal of EVA film using high temperature pyrolysis or by dissolving EVA film using acids, alkali and organic solvents were found effective [38].

5.4.2. CdTe recycling techniques

During thin film delamination is broken down into fragments using two main methods; mechanical and thermal methods Fig. 18 [17,48]. The mechanical methods are laser irradiation, shredding and hammer milling and hotwire cutting. The thin film fragments proceed to the dry and wet mechanical process (attrition) which separates the EVA from the glass and semiconductor material. Attrition is a wet mechanical process using shear and frictional forces on the surface of the particles to be separated. During attrition the thin film fragments are divided into glass, EVA and semiconductors. For this study, it should be noted that impacts from floatation and attrition were added directly to leaching. From literature five different material extraction methods for thin films were found; electrolysis, ion exchange + electro-winning, liquid-liquid extraction precipitation and oxidation reduction [9,50,51]. However,

Table 9
Companies/Union working under recycling of solar panels.

COUNTRIES/ UNION	COMPANY NAMES WORKING UNDER RECYCLING OF SOLAR PANELS
America	FirstSolar, Recycle PV Solar, We Recycle Solarg
European Union	PV cycle ANTEC Solar GmbH SolarWorld Loser Chemie
Japan	New Energy and Industrial Technology Development Organisation (NEDO) NPC
Australia	Reclaim PV
France	Veolia

Table 10
Recycling Approach of different countries.

Country Name	Recycling Approach
Czech Republic	The WEEELABEX organisation which operates out in Czech Republic is responsible for the preparation of standards and the awarding of certification in respect to collection, storage, processing and reprocessing of WEEE and the monitoring of waste-processing companies.
Italy	A significant drive towards the accountable management of the EOL PV modules was the Legislative Decree No. 49 of March 14, 2014 that implements the Directive on WEEE (Directive 2012/19/EU). The Decree also states the minimum aims assuring that at least 75% (by weight) of the modules be recovered, and that at least 65% (by weight) undergo the recycling process. Subsequently, recovery of 80% and recycling of 70% is projected.
North Korea	Still considering waste management regulation for solar PV waste recycling 1. Making manufacturers liable for PV panels EOL would encourage a sustainable management of PV materials [52–55]. 2. Moreover, manufacturers should be encouraged to adopt environmentally friendly designs by enforcing appropriate regulations. This would help to reduce the environmental impact of PV products. It can also be aided by conserving resources through the collection and recycling of EOL products as well as promoting the manufacture of new solar panels by using recycled materials [56]. Finally, strict laws should be passed in relation to the collection and recycling process, which will help the creation of a logistical network to support the productive technology and to create links in an environmentally friendly supply chain.
India	Still considering waste management regulation for solar PV waste recycling.
Thailand	Still considering waste management regulation for solar PV waste recycling.
China	Does not yet have strong policies relating to recycling and even its environmental protection authority has not yet focused on waste recycling.
South Korea	South Korea has just initiated the discussion about PV waste. PV waste is included as one of the Enforcement Rule of Wastes Control Act (Act No. 14783). Article 4.2 outlines complete classifications of waste and possible recyclables.
Japan	In Japan, solar panel waste recycling is under the control of the Japanese environment ministry and solar panel manufacturers participate with local companies in research on recycling technology that relates to recycling technology in Europe.
USA	The state of California DTSC offered to take responsibility for solar waste treatment, when European facilities capacity decreased and the DTSC has now increased its recycling capacity and upgraded their facilities for the disposal of hazardous materials after treatment [57]. USA-based solar panel manufacturing company, First Solar has established factories in the United States, Germany and Malaysia, which also employ recycling methods with recovery rates of 95% for Cd and 90% for glass.
Australia	The Australian government has established the consequence of ensuring that procedures are in place to deal with the issues related to solar PV waste. The decision of the Australian ministry would lead to pioneering systems reducing the environmental impact caused during the lifecycle of solar PV techniques [58].

Table 11
Revenue of commercial recycling processes for Si modules as of October 30, 2019 [47,63,64].

Material	Weight (kg)	Price ($/kg)	Value ($/module)
Glass	13.5	0.06	0.81
Al	1.83	0.95	1.74
Cu	0.11	5.00	0.55
Total			3.10

the scope of this method covers only the delamination and material separation stages which recover over 95% of the PV materials thus the final step was not included in this study [12].

Table 12
Potential revenue by material extraction from a 60-cell Al BSF module as of October 30, 2019, $10.61/module [47,63–66].

Material	% Recovery	Weight	Price ($/kg)	Value ($/module)	% Total
Glass	100	13.5 kg	0.10	1.35	12.7
Al	100	1.83 kg	0.95	1.74	16.4
Polymers	90	1.18 kg	–	0	0
Si	100	0.56 kg	5.52	3.09	29.1
Ag	100	6.5 g	574.23	3.73	35.2
Cu	100	0.11 kg	5.00	0.55	5.2
Pb	100	18.3 g	1.10	0.02	0.2
Sn	100	21.9 g	6.06	0.13	1.2

Table 13
Potential revenue by component extraction from a 60-cell Al BSF module as of October 30, 2019, $18.14/module [47,64,65].

Component	% Recovery	Unit price	Quantity	Value ($/module)	Total %
Glass pane	100	$4.05/$m^2$	1.6m^2	3.25[a]	17.9
Al	100	$0.95/kg	1.83 kg	1.74	9.6
Al BSF cells	100	$0.42/cell	60 cells	12.60[a]	69.4
Cu ribbons	100	$5.00/kg	0.11 kg	0.55	3.0
Total				18.14	100

[a] Recovered components are assumed to sell at 50% of the prices for new components (see Table 5).

5.5. FRELP method proposed by Latunussa et al

The method of recycling modelled by Ref. [6], is acid leaching and electrolysis (Fig. 21). In this method, PV panels are dismantled, glass is refined and separated, and the PV sandwiches are incinerated and cut. The bottom ash from the incinerator is shipped to several facilities to be sent through different processes including sieving, acid leaching, filtration, electrolysis, neutralization, and a filter press (see Fig. 19) (see Fig. 3).

From these recycling steps, the recovery materials of aluminium scrap, silver scrap, copper scrap, and glass scrap are recovered. Liquid wastes, hazardous fly ash, sludge, and contaminated glass produced during the entire recycling process (all waste boxes in Fig. 20) are sent to landfills.

5.6. Recycling process executed by companies

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5.7. Recycling approach of different countries

Under the WEEE directive, all producers or importers of solar PV materials, including solar panels, have to register under a product consent scheme in which all data about the panels must be provided by the manufacturers. Worldwide sixteen recyclers were contacted between 2015 and 2016, of which five European companies (one in Belgium, two in Italy, and two in Germany) provided LCI data [42].

Making manufacturers liable for PV panels EOL would encourage a

Table 14
Comparison of different recycling scenarios: their potential revenue and processing steps [47].

Scenario	No. of processing steps	Potential revenue
Module reuse	3	$22
Component extraction	7	$18.14
Material extraction	9	$10.61

Table 15
Comparison of input parameters of old, recycled and new PV modules.

SR. NO.	Parameter	Old PV module	Recycled PV module	New PV module
1	Rs (ohm)	0.09	0.00522	0.00322
2	Rp (ohm)	1850	2750	3100
3	Ns	36	36	36
4	Q	1.60217646 × 10−19	1.60217646 × 10−19	1.60217646 × 10−19
5	K	1.3806503 × 10−23	1.3806503 × 10−23	1.3806503 × 10−23
6	A	1.185	1.25	1.95
7	Ki	0.0032	0.0032	0.0032
8	Kv	−0.1230	−0.1230	−0.1230
11	Gn	1000	1000	1000
12	Tn	325	325	325
14	Eg	1.12	1.12	1.12
15	Ion (A)	1 × 10−14	1 × 10−15	1 × 10−16

sustainable management of PV materials [52–55].

Moreover, manufacturers should be encouraged to adopt environmentally friendly designs by enforcing appropriate regulations. This would help to reduce the environmental impact of PV products. It can also be aided by conserving resources through the collection and recycling of EOL products as well as promoting the manufacture of new solar panels by using recycled materials [56].

Finally, strict laws should be passed in relation to the collection and recycling process, which will help the creation of a logistical network to support the productive technology and to create links in an environmentally friendly supply chain.

6. Cost of recycling

Recycling the panels can be a crucial pathway, possibly recovering a considerable number of materials and adding economic benefits from currently installed solar panels.

Table 16
Comparison of output parameters of old, recycled and new PV modules.

SR. NO.	Parameter	Old PV module	Recycled PV module	New PV module
1	I_{scn} (A)	2	2.75	3
2	V_{ocn} (V)	40	44	48
3	I_{pvn} (A)	2	2.75	3
4	P_{pvn} (W)	80	121	144
5	I_m (A)	1.7	2.3375	2.55
6	V_m (V)	34	37.4	40.8
7	P_m (W)	68	102.85	122.4

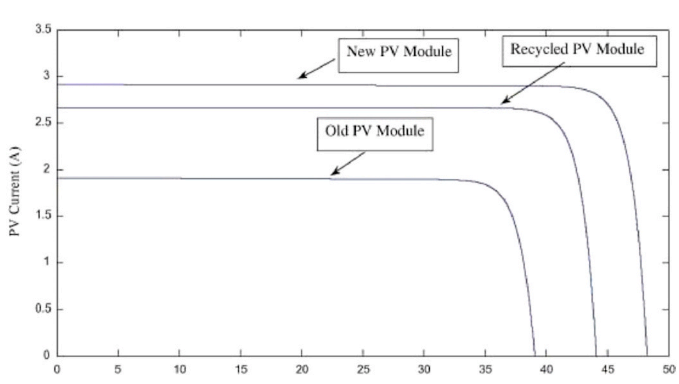

Fig. 25. I–V characteristics of old, recycled and new PV modules at isolation = 1000 W/m^2 and temperature = 325 K [68].

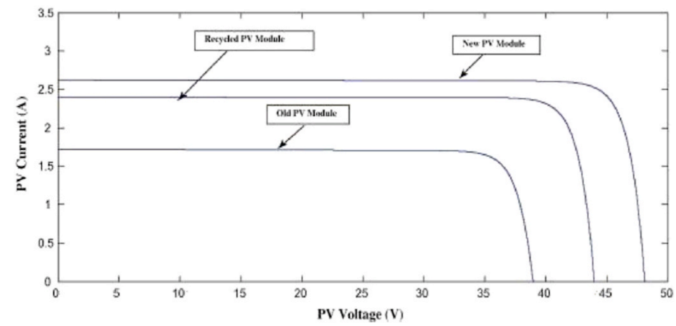

Fig. 26. *I–V* characteristics of old, recycled and new PV modules at Isolation = 900 W/m^2 and temperature = 325 K [68].

6.1. Recycling of crystalline silicon (c-si) PV panels

Costs and benefits considered in the analysis are seen in Fig. 21. The data were broken down in different components: investment costs, process costs, environmental externality costs, recovered material costs, transportation costs, policy benefit costs, and landfilling tipping costs. The functional unit used in this work is 1 m^2 of PV.

6.1.1. Private cost

1. The costs of equipment were taken from manufacturers websites.
2. The transportation costs were found by utilising Latunussa data on distance travelled (km), averaging diesel cost, and estimating average semi-truck fuel efficiency.

External cost: The environmental externality cost (E.C) data were estimated by multiplying the emissions from the recycling process with the damage cost per mass of emissions

E.C = Emission (kg) X Damage cost ($/kg) [60].

6.1.2. Result: private cost of recycling

1. The total EOL cost of 1 m^2 of c-Si PV module was found to be $ 6.72/m^2
2. Disposal + Transportation cost + (Investment + Process) = $ 6.72/m^2
3. The disposal cost of c-Si PV waste is made up of the tipping fees for four materials such as contaminated glass, fly ash, liquid waste and sludge (Fig. 22) in landfills. For every 1000 kg of PV panels processed, 374.4 kg of waste is produced [6].
4. In the FRELP recycling method, diesel fuel, electricity, HNO_3, water, and $Ca(OH)_2$ were consumed during the recycling process of c-Si PV modules.

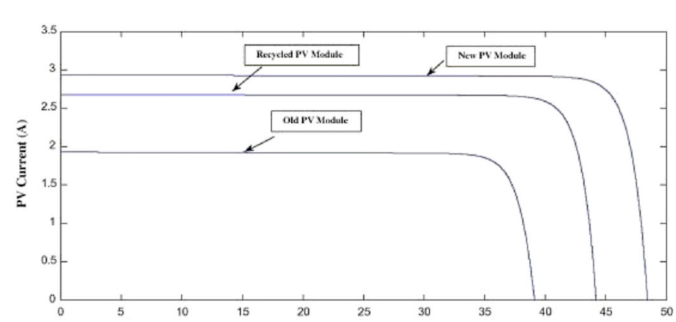

Fig. 27. I–V characteristics of old, recycled and new PV modules at isolation = 1000 W/m^2 and temperature = 330 K [68].

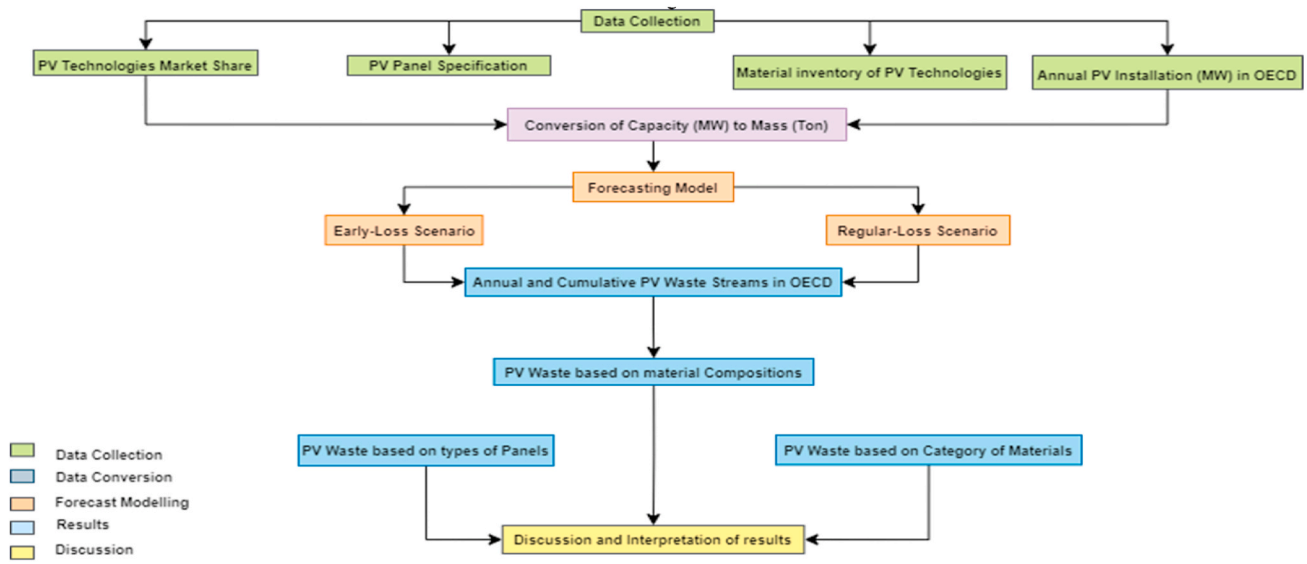

Fig. 28. Approach to estimate PV panel waste [69].

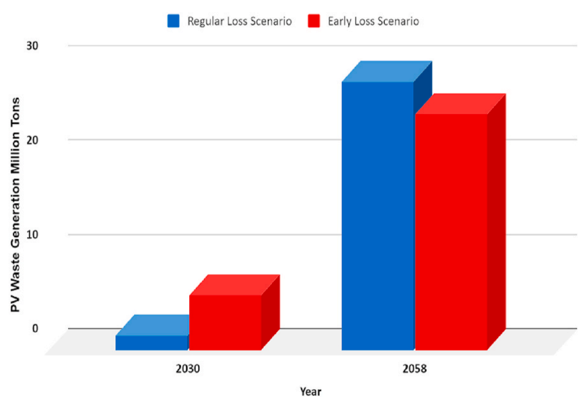

Fig. 29. OECD PV waste generation considering regular and early loss scenario.

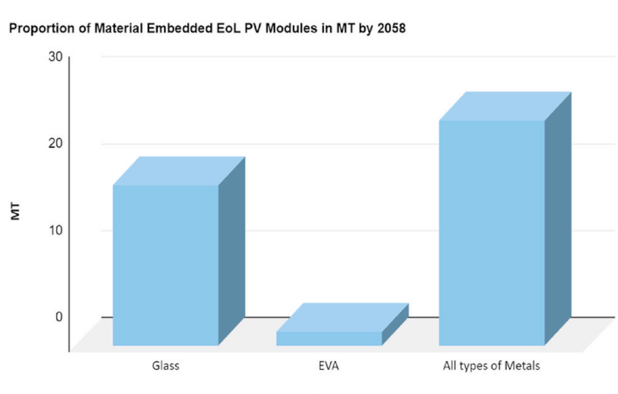

Fig. 30. The proportion of materials embedded in EOL PV modules in MT by 2058.

6.1.3. *Cost–benefit analysis of recycling*

Fig. 23 offers a cost–benefit analysis on recycling c-Si PV modules in their EOL. The negative cost values (benefits) show the revenue that can be realised from the PV waste, while the positive cost values indicate the private and external cost of PV EOL management.

The recycling process is a net benefit to society, even when we include the externality costs of recycling. The total cost of c-Si recycling, including both private and external costs, is \$ 12.43/m^2 without considering the benefit from recovered materials. When this benefit is added, the cost or more accurately the benefit is \$ 1.19/m^2, meaning there is still a benefit from recycling c-Si PV even when the externality costs of recycling are considered. The total cost of PV recycling we found is \$ 1.19/m^2, meaning that it is cheaper to recycle and use PV panels made from recycled materials than it is to throw these materials away at their end-of-life and use virgin materials.

The author also analysed the cost of waste c-Si PV waste and reported that the cost of c-Si PV recycling varies from 8.8 to 20.9 EUR/m^2 (assuming that the c-Si PV module weighs 16 kg/m^2). The higher benefits in the author's result can be explained due to the modelling approach of disposal and transportation.

Adamo et al. ignored the tipping fees and cost of transportation and only modelled the cost of the recycling process for the net economic benefit. If we performed the same analysis as author, our result would show a \$ 13/m^2 benefit, which is consistent with author's result [61].

Comparing the cost of virgin materials to recovered materials, one final comparison which is important to note is the difference in the private and external costs for virgin materials vs. recovered materials (Fig. 24). In Fig. 23, we estimate the value of the recovered materials as \$ 13.62/m^2 but, in Fig. 24, the cost of the virgin materials is about\$ 90/m^2 [62]. Main reasons for recovered material and virgin material calculations are different from each other is because the recycling process is not able to fully recover all the valuable materials, which makes recovered material payback cost unavoidably lower than virgin material cost. Virgin material cost includes machinery and equipment needed for material extraction, while recovered material cost does not, as recovery does not bear these costs.

Overall, it is clear that recycling process is better than usage of virgin materials for manufacturing of PV panels.

6.2. *Potential revenues*

The potential revenue for each recycling scenario is estimated. It is shown that the simplest recycling process generates the highest revenue, and the most complicated process produces the lowest revenue.

6.2.1. *Potential revenue by material extraction*

The materials that should be extracted from Si modules include bulky materials (glass cullet, Al frame, and Cu wiring), valuable materials (Ag and solar-grade Si), toxic material (Pb), and Sn (see Table 11). Table 12

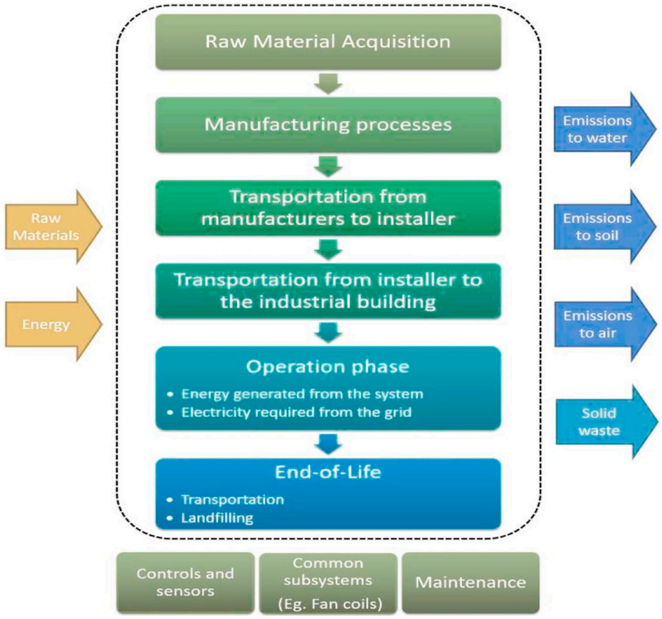

Fig. 31. Life Cycle Assessment boundaries [81].

1) Ground usage: To set up solar panels on a commercial scale, a large portion of land is required which then cannot be used for any other purpose, loss of habitat in that area. However, it can be minimized by usage of barren lands or abandoned places.
2) Pollution: Solar energy being a renewable form of energy emits no CO_2 during its working life. But to produce the panels and transport we require energy for which we require fossil fuels and other forms of energy which produce CO_2. We cannot make complete cycle pollution free but it drastically reduces the CO_2 emission which is produced in comparison to energy generation from fossil fuels and other forms of non-renewable energy. Chemicals should be properly treated and proper disposal arrangements should be made to avoid groundwater pollution and soil degradation.
3) Excess water usage: Manufacturing process water in production of photovoltaic components. CSP requires water for cooling. So, the location of such thermal plants should be at locations which don't have scarcity of water. However dry-cooling can be the best solution as it reduces water usage to a maximum level but it has its own drawbacks.
4) Hazardous waste: Silicon being non-toxic in nature has a greater advantage over other technologies which use toxic material. But after EOL silicon needs to be disposed of in landfills if not recycled which created a major problem. During the manufacturing and recycling process different chemicals are used such as hydrochloric acid, nitric acid, sulfuric acid, acetone and many other chemicals if not disposed of or treated properly can harm the environment in many ways. Thin film technologies consist of toxic materials like cadmium telluride, gallium arsenide, CIGS, etc., if not disposed properly then it can pose a serious threat to the environment in the near future.

shows the potential revenue if all these materials were extracted in their pure, high value forms as of October 30, 2019, summing to $10.61/module. This is the maximum revenue if only materials are extracted from Si modules. The extracted Si is assumed to be solar-grade Si and sold as second-grade solar Si. The EVA layers and backsheet are not recovered, but they can serve as a heat source and reduce the energy needed for pyrolysis of the EVA and backsheet [67]. 100% recovery rates are desirable for all the materials except Si, which is limited to 90%. This is because to recover Si as solar-grade Si, the emitter and BSF in the cells must be removed , thus capping the solar-grade Si recovery rate to 90% [45]. The most valuable materials from Si modules are Ag, solar-grade Si, Al, and glass. Ag and solar-grade Si account for about 65% of the potential revenue. Today's recycling processes recover only low-quality glass, Al, and Cu for $3.10/module (Table 12), so they miss 70% of the potential revenue (see Table 13) (see Table 2).

6.2.2. Potential revenue by component extraction

Component extraction promises a higher revenue than material extraction. Table 6 shows that the potential revenue, if the glass panel and all the 60 Al BSF cells are extracted intact and reusable, is $18.14/module. This is a 71% increase in revenue from material extraction. In this table, it is assumed that the recovered glass pane and Si cells are sold for only 50% of the prices for newly produced glass panes and Si cells (see Table 7).

6.2.3. Potential revenue by module reuse

New 60-cell multicrystalline Al BSF modules produce about 275 Wp per module under standard test conditions (see Table 14). These new modules are sold for a spot price of $0.20/Wp18 or $55/module today. If the decommissioned modules are sold at 50% of the price for new modules, each such module is worth $22/module. Table 15 shows comparisons among three recycling scenarios: component extraction, module reuse, and material extraction. It is clear that as the number of processing steps increases, the potential revenue decreases. This is an important message: products are usually worth more than the components they are made of, and components are worth more than the materials they are made of. From a profitability point of view, module reuse should be the first option, component extraction second, and material extraction last [47].

7. Efficiency comparison: new-existing-recycled

Efficiency comparison between new, recycled and existing modules has been carried out using data given below and IV characteristics curves are represented with conclusion.

On the basis of simulation of all three PV modules (i.e., old, recycled and new) the output parameter is given in Table 15 and 16. The output parameters Im, Vm and *Pm* are the current, voltage and power at maximum power point, respectively.

7.1. Result and discussion

Fig. 25 show the I–V characteristics of old, recycled and new PV modules at isolation = 1000 W/m^2 and temperature = 325 K. Fig. 26, show the I–V characteristics of old, recycled and new PV modules at isolation = 900 W/m^2 and temperature = 325 K.

Fig. 27: show the I–V characteristics of old, recycled and new PV modules at isolation = 1000 W/m^2 and temperature = 330 K.

Figs. 27 and 28, Fig. 29, show that old PV module is recycled to new PV module with an increase in voltage, current and power. About 90% of power is recycled from old PV modules as compared with new PV modules.

Recycling is attempted to develop a safe and cost-effective process for the disposal of PV solar panels. Reclaiming of such materials keeps precious natural resources from being depleted. Now companies can see the potential benefits out of recycling of PV panels [68].

8. Waste composition and generation

A recent statement found that Toshiba Environmental Solutions will take approximately 19 years for reprocessing all the solar enormous waste of Japan produced by 2020. The yearly waste will be 70 to 80 times more by 2034 than in 2020. China, with a huge number of solar plants, currently operates around two times as many solar panels as the USA and has no proposals for the dumping of the whole old panels. In spite of the presence of environmental awareness, California, another world leader in solar panels, also has no waste disposal plan. At the end of their useful lives, only Europe needs the manufacturer of solar panels to collect and dump solar waste. Although solar panels were disposed of on regular sites, it is not advisable because the modules can degrade, and harmful chemicals can leach into the ground causing drinking water contamination.

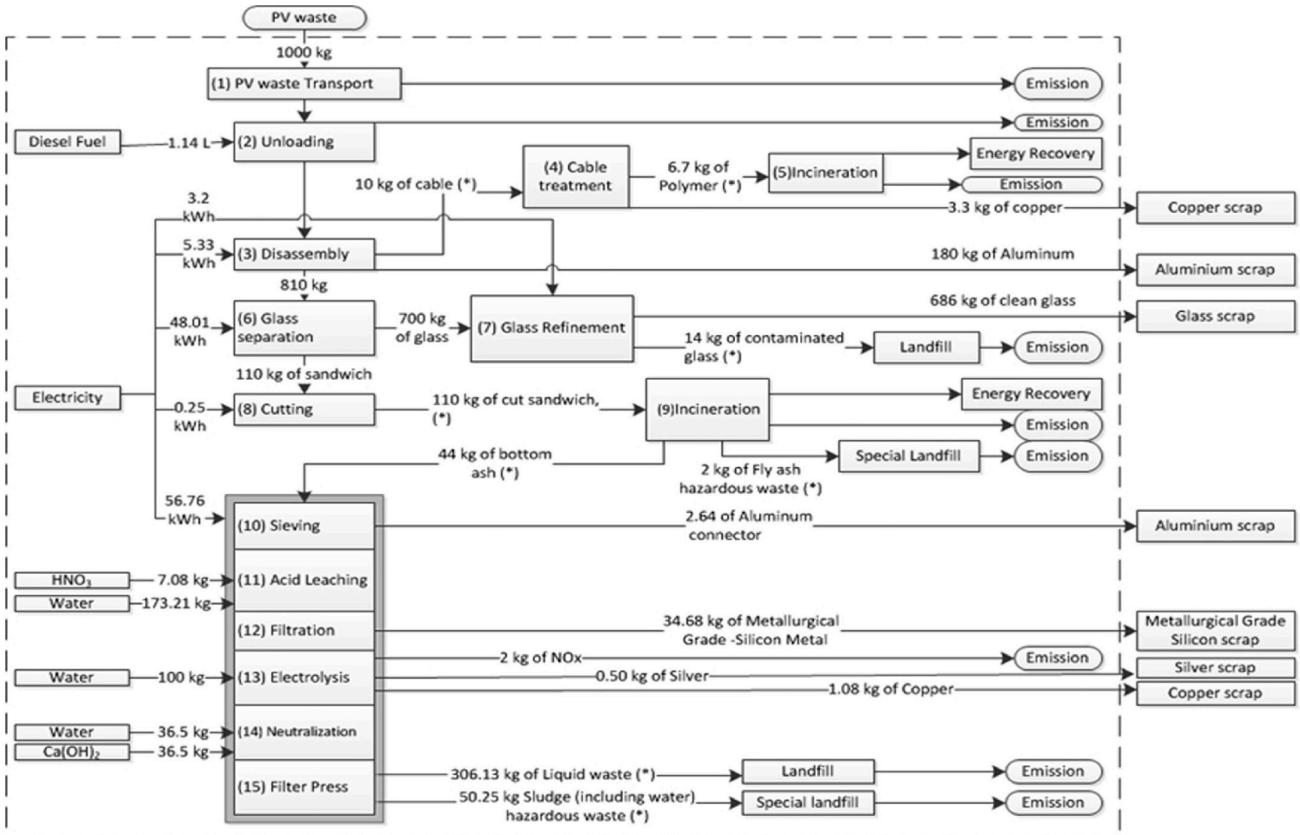

Fig. 32. System boundaries of the LCA of the silicon PV waste recycling process (transport between the process is highlighted with an asterisk (*) [6].

Table 17
Quantification of metals embedded in the OECD PV waste flow [69].

Material Category	Net Mass Million	% Net Mass
Precious Metal (PM)	0.0130	0.18
Hazardous Metals (HM)	0.0075	0.11
Critical Substances (CS)	0.125	1.76
Other metals (OM)	2.37	33.3
Base and Special Metal (BSM)	4.58	64.6

Table 18
Estimated materials composition of PV waste in OECD by 2058 scenario [69].

Materials and Substances	Mass (Tonne)	%
Glass	18,610,039	68.10%
Al	3823,857.96	13.99%
Steel	2179,785.90	7.98%
EVA	162,4719.63	5.94%
Ni	359,799.72	1.317%
Cu	248,105.03	0.908%
Si	185,716.22	0.680%
Fe	137,428.58	0.503%
Mg	120,391.49	0.4405%
Ti	12,962.994	0.0474%
Cd	7771.51	0.0284%
Cr	5480.29	0.0201%
Te	4448.86	0.0163%
Mo	3237.14	0.0118%
Se	1161.45	0.0042%
Sn	858.46	0.0031%
Zn	813.69	0.0030%
Ga	771.40	0.0028%
Pb	759.96	0.0028%
In	758.20	0.0028%
Mn	387.20	0.0014%
Ag	6.44	0.000024%

The study indicates the comparison of the estimated cumulative PV waste volumes in OECD based on early-loss and regular loss scenarios. It is apparent that the c-Si panel is the dominant PV waste technology throughout the period and very few for other types of PV modules. Regular-loss scenario reveals that the projected decommissioned PV module accounts for 33,258 tonnes by 2019 with a rise estimated to 1.53 MT by 2030. An even more significant increase to almost 28.4 MT can be expected by 2058. The PV waste projection by early-loss scenario forecasts a much more drastic rise in overall early cumulative PV waste streams, with 617,166 tonnes alone by the end of 2019. These projections would increase to 5.75 MT by 2030 and a total of 24.98 MT by 2058, as the early-loss scenario assumes a higher percentage of failures than the regular-loss scenario [69].

8.1. Quantifying of PV waste material flow in OECD

Base and special metals: Al, Cu, Ni, Fe, Ti, Sn, Zn, Cr, Mn, Mo; Critical substances: Mg, Ga, In, Te; Hazardous metals: Cd, Pb, Se; Other metals: Si, Steel; PM: Ag Table 19 provides the estimated cumulative volume of PV waste materials and substances in OECD countries by 2058 based on the regular-loss scenario (see Table 17). Fig. 30 provides a comparison of all metals and non-metals materials embedded in EOL PV modules in MT by 2058.Table 18 categorizes the OECD PV panel waste metal stream into four major classes. It is revealing from the results that the sustainable handling of this enormous number of wastes requires dynamic development of an integrated PV waste management technique providing a domestic or regional PV recycling industry (see Table 20) (see Figs. 31 and 32).

8.2. Waste projections by country

PV panel waste projected by different countries are mentioned in Table 6 from 2016 to 2050. The projections are modelled using the same

Table 19
Modelled results of estimated cumulative waste volumes of end-of-life PV panels by country (tonne) [5].

Year	2020		2030		2050	
Scenario (regular-loss/early -loss)	Regular loss	Early loss	Regular loss	Early loss	Regular loss	Early loss
China	8000	100,000	200,000	1,500,000	13,500,000	19,900,000
Japan	15,000	100,000	200,000	1,000,000	6,500,000	7,600,000
India	2000	15,000	50,000	325,000	4,400,000	7,500,000
Germany	20,000	200,000	2,200,000	2,600,000	4,300,000	4,300,000
United States of America	13,000	85,000	1,700,000	4,000,000	7,500,000	10,000,000
Australia	2000	17,000	300,000	450,000	900,000	950,000
Total World	43,500	100,000	850,000	1,700,000	60,000,000	78,000,000

Table 20
Health impacts of excessive generation of solar waste.

AUTHORS	
[75]	Higher concentration of the PAH metabolites among people exposed to dismantling PVs than people who are indirectly exposed thereby risking lung infections
[76]	PV modules contain hazardous materials like cadmium, selenium, tellurium, lead, most countries place strict regulations due to the level of its toxicity to fish, wildlife and humans
[77]	Cadmium remain in the environment for many decades, is attributed to many illnesses such as increased blood pressure, peripheral artery diseases, pulmonary impairment, renal dysfunctions, bone changes
[78]	Water used for cleaning purposes in the recycling process contains can cadmium which in turns dissolves into ground water by leaching process.
[72]	Lead (Pb) poisoning can lead to a multitude of complications in the form of eye, kidney and brain damages, can cause burns and could lead to reproductive disorders

Table 21
Chemical used in process and their health and environmental impact [79].

CHEMICALS	PURPOSE	HEALTH AND ENV IMPACTS
$(CH_3)_2CO$	Cleaning out microscopic dirt and dust-off chips.	Eyes and nose irritation, throat infection, kidney and liver problems, nerve damage, birth defects and sexual problems including lower ability to reproduce in males.
NH_3	Production of antireflective coatings	Skin and eyes irritation, throat and lungs infections, mouth and stomach burns
As	Production of GaAs solar PV cells	Toxic and carcinogens, heart and liver problems, lung cancer, throat infection, nausea, vomiting, reduced blood cells, dark and red spot on skin, hands and feet etching
Cd	Manufacturing CdTe solar cells	Toxic and carcinogenic, kidney, prostate and respiratory system infections, diarrhoea, and lung cancer.
HCl	Production of electrical grade silicon, clean and etch semiconductors	Skin irritation, eyes, nose, mouth and throat infections, food digestion, and respiratory depression.
H_2	Manufacturing a-Si solar cells.	Flammable and highly explosive.
Pb	Wiring and welding photovoltaic electrical components	Carcinogenic, brain, kidneys and nervous system damage, weakness in bones, anemia, and miscarriage.
HNO_3	Cleaning and removing dopants from wafers and reactors	Chemical burns.

Weibull function parameters as the global estimates of the previous section. Estimated waste volumes of PV panels in different countries are based on existing and future annual installations. The historic cumulative installed PV capacity was used as a benchmark for future projections to 2030 using IRENA's REmap and for 2030 to 2050 IEA's PV Technology Roadmap, with a simple interpolation [5].

9. Environmental impact

9.1. Recycling-environmental and safety impacts

The environmental impacts of recycling solar PV materials are noteworthy. Hazardous chemicals potentially affect health and the environment. Several researchers have contributed enormously to Life cycle assessments to analyze the potential environmental impacts. Author estimates that the recycling process requires a large volume of water, excessive heat and electricity and contributes roughly 43% to the total global warming process scenario. It is also evaluated that in the panel production stages, the acidification potential is approximately 36%.

They conclude that CdTe technology is more energy efficient and consumes fewer resources as compared to Si technology [70]. On the production side, Muller et al. attribute the glass and metals contributes towards environmental impact and estimates 70% energy reduction in the thermal recycling of the thermal silicon wafers as opposed to primary production [71].

Batteries are considered to be the most hazardous of all the components in the solar PV system during EOL. Lead–acid batteries are extensively used due to their availableness and pricing, though they are not recommended for solar energy storage. They are also listed as the top ten causes of industrial pollution [72]. Nearly all components of a lead–acid battery are recycled where the plastic recycled can be re-used for battery casings and the lead extracted can be reused in the battery. The recycling of lithium batteries leads to recovery of nickel, cobalt, copper and other materials [73].

9.2. Environmental impact

9.2.1. Health impacts

The difficult part is the exposure risk either during disassembly of the products or during burning, which comprises heavy metals, polychlorinated biphenyls, polyvinyl chloride, wire casings, circuit board contents [74]. Different kinds of health problems caused by different techniques of processing and use of different chemicals are mentioned below.

9.3. Life cycle interpretation and discussion of the results

The LCIA results show that for all the considered impact categories, the main contributions are related to the transport of the PV waste to the site, the incineration processes, and the further metal recovery from the bottom ash (including sieving, acid leaching, electrolysis, neutralization and filtrations). For example, the overall climate change impact of the process amounts to around 370 kg CO_2eq. This is mainly due to transport (29%), the incineration of the PV sandwich (34%) and the metal recovery treatments (24%).

The contribution of the transport to the different impact categories is generally relevant, and it is ranging from a minimum of about 10% (for the freshwater ecotoxicity) up to 80% (for the abiotic depletion potential

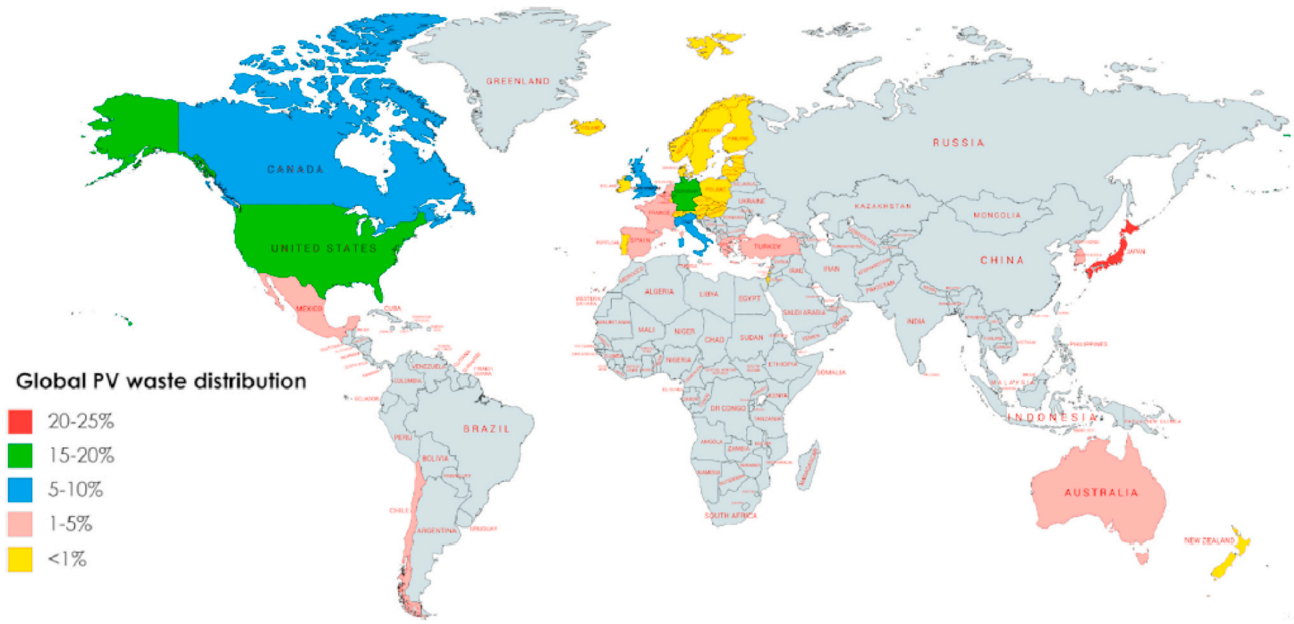

Fig. 33. The distribution of PV waste stream in OECD countries based on the panels installed between 2000 and 2018 [69].

Fig. 34. The estimation of the suitable time to initiate the recycling business by assuring economic profitability of treatment [69].

– minerals) [6].

9.4. Timescales for designing markets and circular economy

Economic assessment papers by authors discussed that the number of annual 20 kg tonne EOL panels can fulfil the business viable requirements of EOL PV waste management in terms of waste volume required (see Fig. 33). Thus accordingly, Fig. 34 shows the probable year to start the business for each OECD country based on the regular loss scenario. The results certify that there are twenty-one countries which will not be able to meet the minimum feasibility factor to run the PV plant for the recovery and treatment purposes individually until the year 2060 without increasing the installation rate from 2020 onwards. These countries need to join the other OECD countries for EOL PV waste treatment. Besides, it can be understood from the column chart that none of the member countries will generate enough PV waste volume until 2025. Thus, the short-term solution to initiate the PV waste treatment in OECD earlier is to start and run a JTP based on the proximity of the PV waste destination and origin countries, standard of the infrastructure and technologies [69,80].

10. Conclusion

Solar energy has recently become an important renewable energy source. It helps significantly reduce the carbon footprint compared to other methods of power generation. Every coin has 2 sides, everyone recognizes the benefits emerging solar technologies bring, rather there is a vast scope in this field to make solar technology more efficient, cost effective and reduce the waste generation by introducing or working on newer technologies. The other side is where the Researchers, Policy makers, Industries, and Government should focus upon. In the upcoming decade, waste generated due to solar technology is going to rise exponentially and the world should be ready to tackle that issue so that solar technology doesn't turn out to be banned from society just like plastic.

This review paper provides an overview of currently available solar technologies, efficiency comparisons, and different types of recycling methods. The main focus of this paper, intended to help the reader to understand the methods available and how they can be improved. Generates solar energy with a larger field sustaining front. This study contributes to the literature assessing the sustainability of the EOL management of PV panels, and paves the way for future researchers to comprehend the issues involved in the sustainable development of the PV sector. We recommend that recycling should be made commercially necessary by making manufacturers responsible for recovering materials from solar PV panels EOL [8].

The amount of aluminum in crystalline Si PV modules is about one-fifth of the total mass, but its economic value is equal to two-thirds of total revenue. After aluminum, glass is characterized by low market value but high quantity. Finally, the most valuable material in crystal modules is copper, accounting for 9% of total turnover, while its content accounts for 1% of total mass. Analysis of cost distribution is greatly influenced by collection and collection process. Together, these two items have a percentage weight greater than 90% [61]. The universal recycling process for all Si solar cells includes two main steps: using 30% aqueous KOH for removing Al metal coatings (temperature 60–80 °C, time 2–3 min) etching using the mixture: 250 ml HNO_3 (65%): 150 ml HF (40%): 150 ml CH_3COOH (99.5%) þ 3 ml Br_2 for removing Ag coatings, ARC and n-p junctions (temperature 40 °C, time 9 s) [43].

One is sequential electrowinning which allows multiple metals to be recovered one by one from Si modules, Ag, Pb, Cu and Sn. The recovery rates of Ag and Cu are currently 74% and 83%, respectively, but can be increased to 95%. The purity of the recovered metals is above 99%. The other technology is sheet resistance monitoring which maximizes the amount of solar-grade Si recovered from the modules. Over 90% of the Si in the original modules can be recovered, and the recovered Si meets the specifications for solar-grade Si. The revenue can eliminate a major obstacle to Si module recycling, enabling a profitable recycling business without any government support. Based on the current solar panel distribution network, we propose a waste solar panel collection network to reduce collection costs. Future work will include improving recovery rates of the metals and replacing the Pt counter electrode with a low-cost alternative [45].

Main focus of this paper was to provide the reader the overall information in one paper, which will help them understand the present scenario in this field.

CRediT authorship contribution statement

A. Divya: Writing – original draft, Investigation, Data curation. **T. Adish:** Writing – original draft, Methodology, Formal analysis. **P. Kaustubh:** Writing – original draft, Resources, Investigation, Conceptualization. **P.S. Zade:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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