

## **Chapter 5**

### **EXPERIMENTAL & END LIFE ECONOMIC ANALYSIS OF BSDU 160 kW SOLAR PV PLANT**

This chapter outlines the experimental analysis of the 160 kW grid-connected solar power plant installed at the BSDU Jaipur campus. Economic analysis of the photovoltaic plant from origin to end-life management is put forward. Recovery of elements along with the complete beneficiary outcome is assessed. Transportation cost is also included in the overall end-life management analysis of the plant.

#### **5.1 Introduction**

Modern times have involved the surplus use of solar photovoltaic technology in the energy sector. India is incredible in its energy source category be it renewable or non-renewable sources. The average solar insolation of India is 5,000 T kWh per year (i.e. ~ 600 TW), major insolation accounts for states like Gujarat, Telangana, Rajasthan, etc. 23.30 to 30.12 North latitude and 69.30 to 78.17 East longitude locates Rajasthan. Annually it receives 6-7 kWh/m<sup>2</sup> solar irradiance each day. 5109.96 MW of the total solar installation has been already done in Rajasthan and further wider opportunity is available. End-life recycling monetary aspects along with material recovery are also put forward.

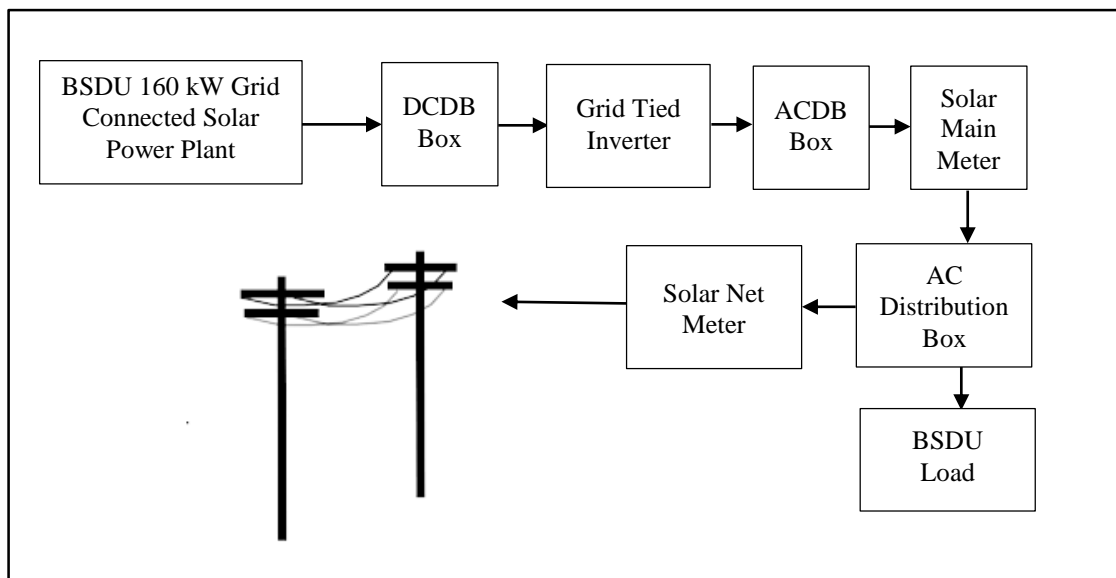
The current report focuses on the origin (2017) and retirement (2042) evaluation of 160 kW on grid rooftop solar PV plant installed in Bhartiya Skill Development University Jaipur Rajasthan. End-life responsibilities should be taken care of by the manufacturers to facilitate the steps for easy and economic recycling and also to eradicate toxic components. This will be promoting the onset of an independent & sustainable society in the crisis era of fossil fuels.

#### **5.2 Experimental Analysis of BSDU 160 kW Solar PV Plant**

In the present century with the accelerating energy consumption, renewable sources of energy are being used. In India, most areas receive solar irradiance of approximately 4.7 kWh / m<sup>2</sup> / day and its land mass is expected to receive approximately 5000 trillion

kWh of solar energy per annum. With the promotion of the Jawaharlal Nehru National Solar Mission from the year 2010, the installation of solar photovoltaic systems in India received an exponential upsurge (Raina & Sinha, 2019). In this paper, a 160 kW grid-connected solar rooftop panel installed in Bhartiya Skill Development University Jaipur Rajasthan is studied. BSDU is a skill-based university established to achieve the principle of Aatma Nirbhar Bharat located in the Mahindra World City, off Ajmer highway Jaipur Rajasthan.

Even though with aim of provision of electricity to every niche of India still the variation in the electricity bill is reported in areas of Rajasthan in terms of energy tariff. This particular issue can be pulled out by the usage & installation of a Grid-connected solar photovoltaic system. This grid-connected solar photovoltaic system when generates excess electricity rather than load requirement (Baitule & Sudhakar, 2017). It feeds the extra electricity to the grid and when the same grid (on-grid) produces less electricity than the load requirement it takes the surplus electricity from the grid to full fill the load demand (S. Chakraborty et al., 2015).



**Fig.5.1** BSDU 160 kW Grid Connected Solar Power Plant.

A 160 kW grid-connected rooftop solar photovoltaic system based on monocrystalline silicon solar panels in BSDU is evaluated here. This system comprises of solar panel, inverter, battery, mount structure & storage battery. In the rooftop grid-connected plant the panels are anchored on a 0° azimuth angle and 26° inclination leaning towards the South (Khatri, 2016). During installation, panels are mounted in the shade-free area.

320Wp rated Anchor Panasonic crystalline silicon panels are utilized. The mechanical properties of solar panels of the proposed solar plant are mentioned underneath in Table 5.1. These panels are resistant to harsh weather conditions like salt, mist, dust, corrosion, and shadow (Smith & Bogust, 2018).

**Table 5.1** Mechanical Properties of 320-Watt Anchor Panasonic Solar Panel

Solar Cell	Polycrystalline silicon 156 X 156 mm (6 inches)
No. of Cells	72
Dimensions	1956 X 992 X 40 mm (77.0 X 39.1 X 1.6 inches)
Weight	25.8 Kgs
Front Glass	4 mm (0.16 inches) tempered glass
Frame	Anodised aluminum alloy
Junction Box	IP67 rated (3 bypass diodes)
Connectors	MC4 compatible
Back Sheet	High resistant polyester
Encapsulating Material	Ethylene Vinyl Acetate (EVA)

The mounted solar panels working efficiency is tested under standard conditions. Aluminum brackets & bolts of steel are utilized to anchor the panels on the roof. Three numbers of 50 kW capacities of ABB string inverter are used and their specifications are mentioned in Table 5.2.

**Table 5.2** Input & Output Side -Technical Data of the ABB Inverter

Absolute maximum DC input voltage (V <sub>max</sub> )	1000 V
Start-up DC input voltage (V <sub>start</sub> )	300-500V (Default 360)
Rated DC input voltage V <sub>dcr</sub>	715 Rated DC input V <sub>dc</sub>
Rated DC input power P <sub>dcr</sub>	51250 W
Number of independent MPPT	1
MPPT input DC voltage range	520-800 V <sub>dc</sub>
Maximum DC input current (I <sub>dcrmax</sub> )	100A
Maximum input short circuit current	144 A
Number of DC inputs strings/pairs	12 or 16 string combiner version available
AC Grid connection type	3-Phase, 440V
Rated AC power	50000W
Maximum AC output power	50000W
AC voltage range	422-528V
Maximum AC output current (I <sub>acmax</sub> )	61 A
Rated output frequency (f <sub>r</sub> )	50 Hz

**Table 5.3** Data for 160 kW BSDU Solar Photovoltaic Plant

Requested Location:	BHARTIYA SKILL DEVELOPMENT UNIVERSITY
Location:	Lat, Lon: 17.35, 78.45
Lat (deg N):	17.35
Long (deg E):	78.45
Elev (m):	0
DC System Size (kW):	160
Module Type:	Premium
Array Type:	Fixed (roof mount)
Array Tilt (deg):	20
Array Azimuth (deg):	180
System Losses:	14.08
Invert Efficiency:	96
DC to AC Size Ratio:	1.2
Average Cost of Electricity Purchased from Utility (\$/kWh):	0.112
Capacity Factor (%)	18.2

### PV watts Software usage on BSDU Solar PV Plant

PV Watts calculator is a useful map-based tool to analyze photovoltaic sites. National Renewable Energy Laboratory designed it. It provides the global annual energy output of grid-connected PV systems. It can also provide PV energy output hourly values. PV Watts calculator can estimate monthly irradiation, annual solar irradiation, energy output in kilowatts, and energy value.

**Table 5.4** PV Watts Monthly PV Performance Data of BSDU Plant

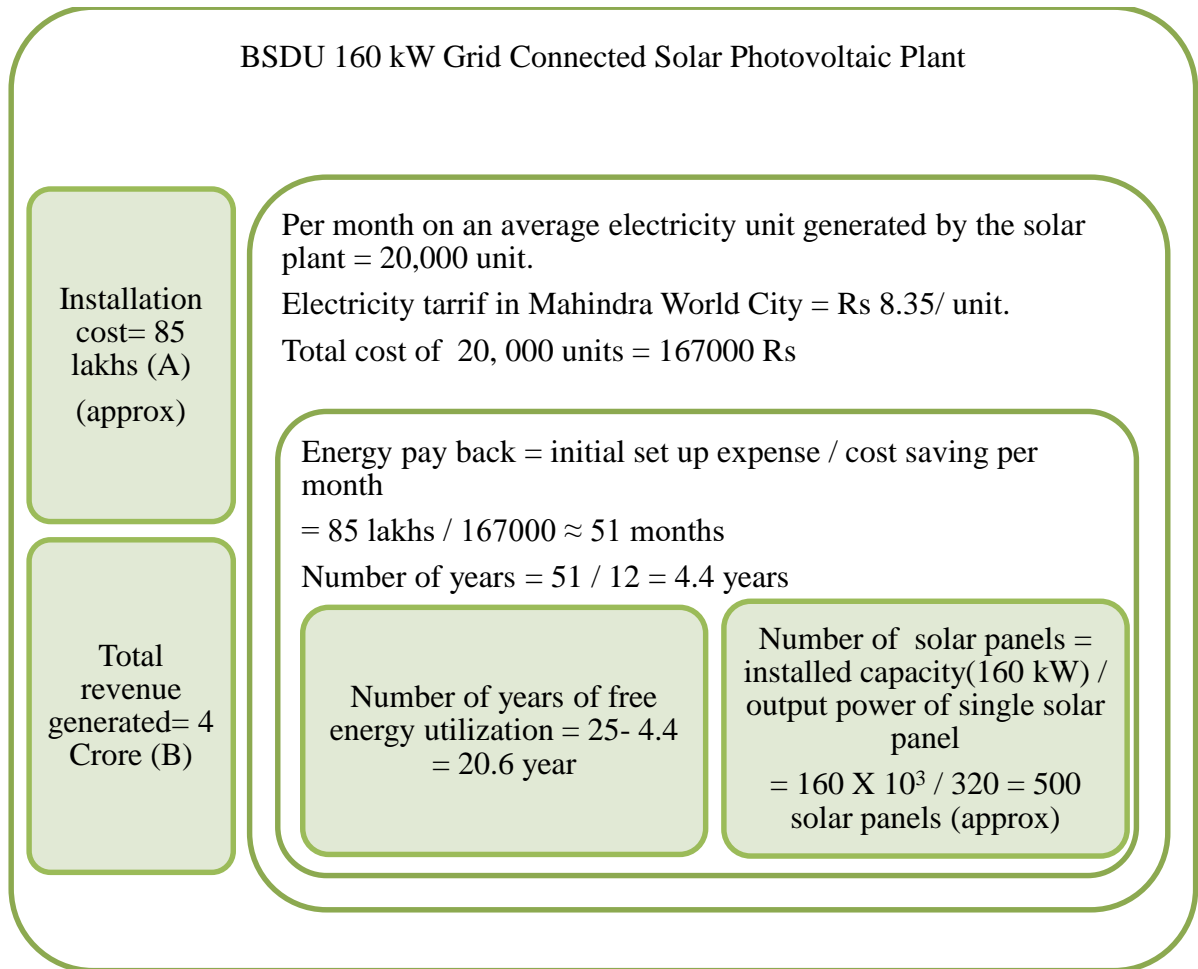
<b>Month</b>	<b>AC System Output (kWh)</b>	<b>Solar Radiation (kWh/m<sup>2</sup>/day)</b>	<b>Plane of Array Irradiance (W/m<sup>2</sup>)</b>	<b>DC array Output (kWh)</b>	<b>Value (USD)</b>
January	22773.38477	6.17809916	191.5210724	23727.32617	2,550.62
February	22172.48242	6.77160549	189.60495	23090.32031	2,483.32
March	24417.92969	6.91705179	214.4286041	25433.05664	2,734.81
April	22560.42383	6.6896224	200.6886749	23511.33984	2,526.77
May	21636.51758	6.05280972	187.6371002	22560.0918	2,423.29
June	18440.75391	5.11215544	153.3646698	19261.15039	2,065.36
July	17792.11914	4.64747906	144.0718536	18599.9375	1,992.72
August	18536.08594	4.89532471	151.7550659	19357.85156	2,076.04
September	20874.33203	5.78081799	173.4245453	21771.92383	2,337.93
October	21737.48828	5.93933105	184.1192627	22677.37891	2,434.60
November	21271.22461	5.98656511	179.5969544	22156.59766	2,382.38
December	22263.65039	6.04605246	187.4276276	23186.70703	2,493.53
<b>Total</b>	<b>254476.3926</b>	<b>71.01691438</b>	<b>2157.640381</b>	<b>265333.6816</b>	<b>28501.4</b>

**Table 5.5** Actual Monthly Data from 160 kW BSDU Solar Photovoltaic Plant

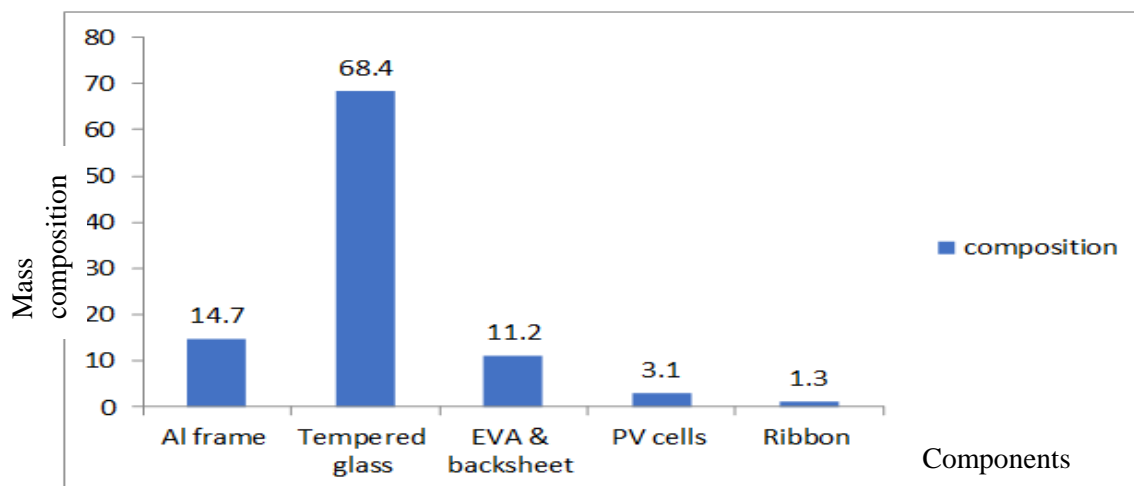
Date	Readings (Previous)	Readings (Current)	Total	Multiplication Factor	Total (kW h)	Readings Per kW / day (kW h)
1/04/2018	413.2	1019.2	606	40	24240	5.21
1/05/2018	1019.2	1606.7	587.5	40	23500	5.22
1/06/2018	1606.7	2210.3	603.6	40	24144	5.19
1/07/2018	2210.3	2735.8	525.5	40	21020	4.67
1/08/2018	2735.8	3157.2	421.4	40	16856	3.62
1/09/2018	3157.2	3548.5	391.3	40	15625	3.36
1/10/2018	3548.5	3982.6	434.1	40	17364	3.86
1/11/2018	3982.6	4535.3	552.7	40	22108	4.75
1/12/2018	4535.3	5018.9	483.6	40	19344	4.29
1/01/2019	5018.9	5523.6	504.7	40	20188	4.48
1/02/2019	5523.6	6027.1	503.5	40	20140	4.3
1/03/2019	6027.1	6560.1	533	40	21320	5.07

### 5.3 End Life Economic Analysis

The total number of solar panels used in a 160 kW solar power plant upon reaching their end life will generate a huge amount of waste. This can be tackled by either recycling through the usage of the Thermal, Mechanical or Chemical process or by dismantling the panels (Contreras Lisperguer et al., 2020; Domínguez & Geyer, 2017; Li et al., 2021). The material market price of recycled & dismantled products also accounts for profit making from the solar plant at its end life (P. Dias et al., 2021; S. Kumar et al., 2020). I.D'Adamo estimated the mass fraction of 1 ton of crystalline Si PV modules (D'Adamo et al., 2017). After the attainment of the end life of the grid-connected solar plant, the amount of revenue generated by the recycling process of the solar panels is denoted as (B). The amount generated from the recycled materials is denoted as C.

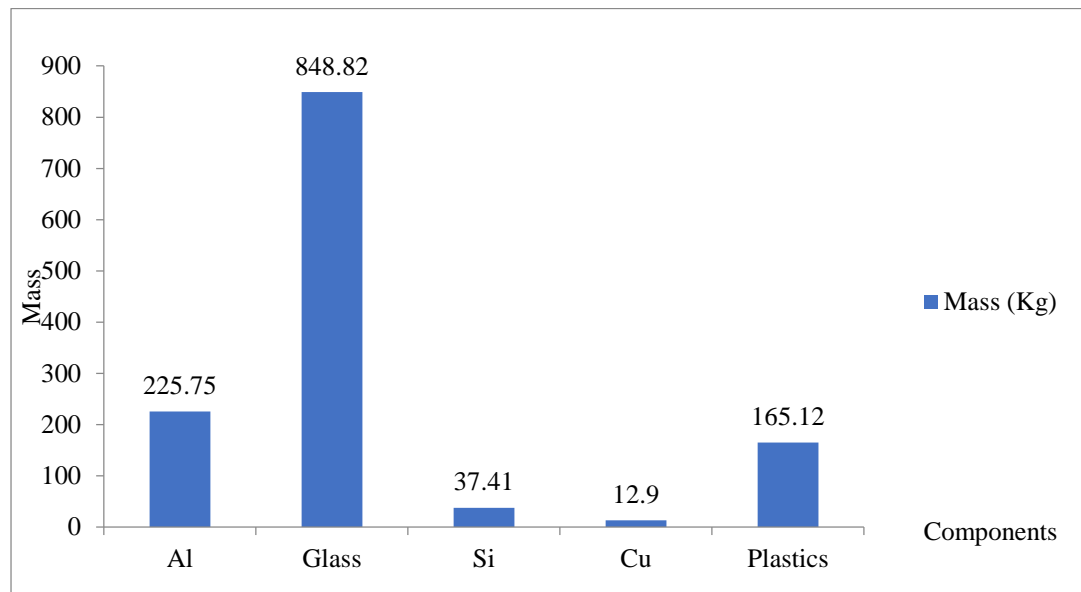


**Fig.5.2** End Life Cost Analysis of 160 kW Grid Connected Solar Power Plant at BSDU



**Fig. 5.3** Mass fraction of the PV Modules in 1 Ton of Crystalline Si PV Module (D’Adamo et al., 2017)

The total panels in the 160 kW BSDU plant weigh 12900 Kg. The mass fraction of this is shown in Fig.5.4.



**Fig.5.4** Mass fraction in Panles of BSDU 160 kW Solar Rooftop Plant

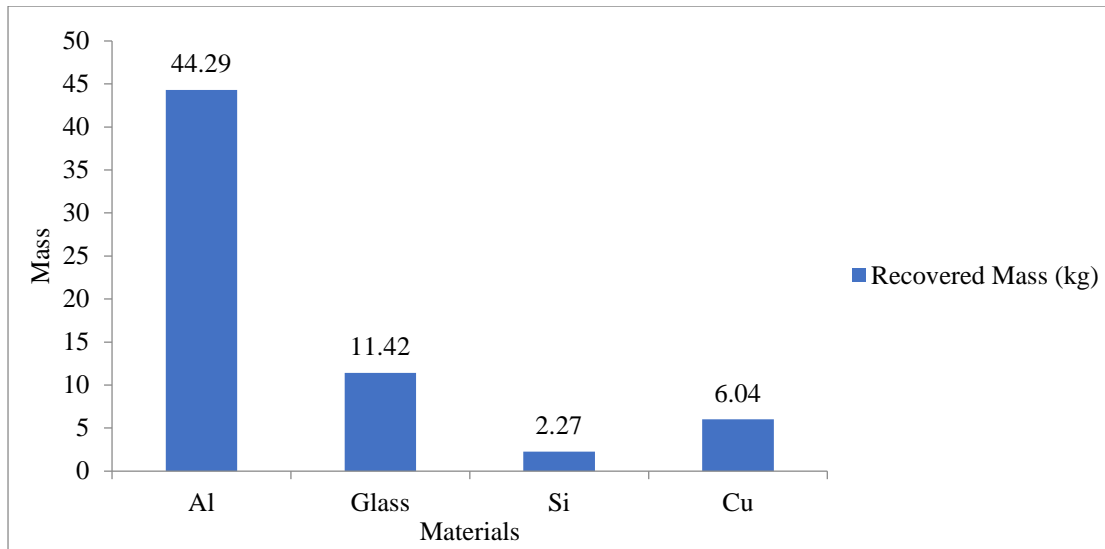
$$\text{Material content (kg)} = \frac{\text{Installed capacity(W)} \times \text{Material Composition} \left( \frac{\text{Kg}}{\text{m}^2} \right) \times \text{Market share (\%)}}{\text{Module Nominal Power} \left( \frac{\text{Wp}}{\text{m}^2} \right)}$$

(D'Adamo et al., 2017)

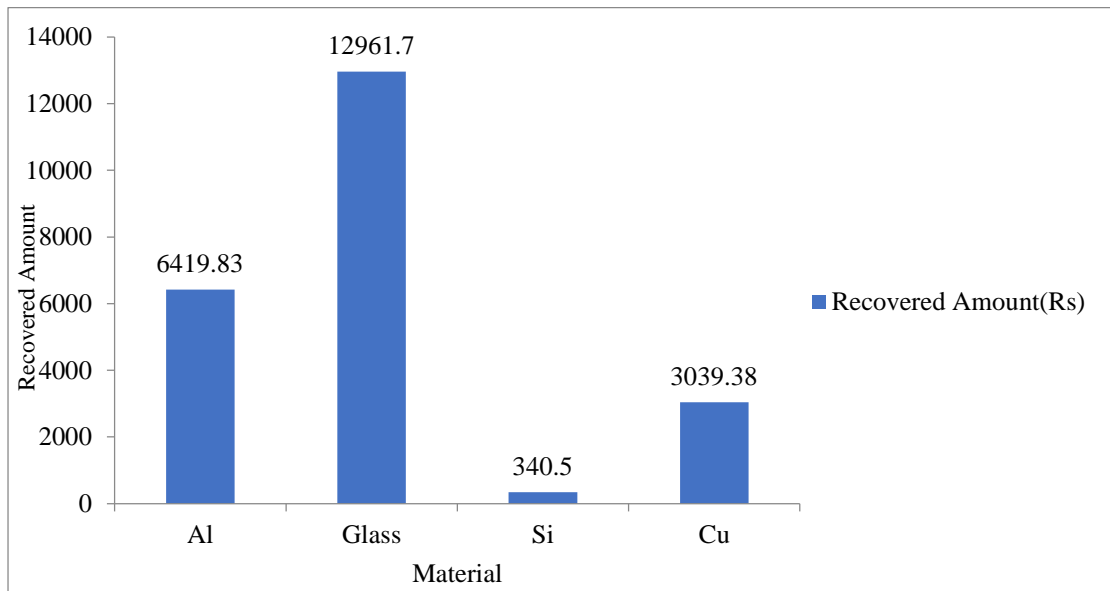
The market share of crystalline silicon panels is 73.30 % for the current year (Weckend et al., 2016). Hence the total material content in the BSDU plant from the above formula is

$$\begin{aligned} \text{Material content (kg)} &= \frac{(160 \times 1000) \times 1290 \times 73.30}{320} \\ &= 47,278,500 \text{ Kg (four million, seven hundred twenty-five thousand)} \end{aligned}$$

Recovery yield from the 160 kW plant for Al is 100%, Glass is 97%, Si is 85%, Cu is 78% & plastics include ethylene vinyl acetate layer which is not considered in the calculation part due to its fractional recovery compared to others (Celik et al., 2018; P. Dias et al., 2021; Klugmann-Radziemska, 2012; Yi et al., 2014). The market price of each recovered element is explored for (*Aluminium Price / MCX Aluminium - Aluminium Rate in India Today Live on The Economic Times*, n.d.) The recovered amount is estimated to be approximately a total of Rs. 22815. Recovered mass fraction & individual amount of the panel material through recycling is shown in Fig. 5.5. & Fig. 5.6.



**Fig.5.5** Recovered Mass from Panels of 160 kW Grid Connected Plant in BSDU



**Fig.5.6** Recovered Amount of Material from Panels of 160 kW Grid Connected Plant in BSDU

Henceforth the total savings in terms of profit = B+ C- A = D..... (1)

However, in this calculation only the recycling recovery cost is taken, if the recovery of materials by dismantling is also added to it then further the cost-benefit will be increased more (Maani et al., 2020; Markert et al., 2020). Overall profit is 31,522,815 Rs approximately (Thirty-One Million, five hundred twenty-two thousand, and eight hundred fifteen). Value can be generated from the solar photovoltaic waste by their recycling at end life. Recycling techniques need to be practiced at a commercial scale to recover the valuable materials as it will boon the employment sector by establishing a recycling industry and a further new industry will be set up to utilize the recycled

materials.

When the solar panels on the 160 kW solar power plant approach the end of their useful life, a significant amount of garbage will be generated. This can be handled by either recycling the panels via a thermal, mechanical, or chemical technique, or by removing the panels. It is also possible to calculate the benefit derived from the solar plant at the end of its useful life based on the market price of recycled and dismantled products (Li et al., 2021). I.D'Adamo and colleagues (Contreras Lisperguer et al., 2020) estimated the mass fraction of a ton of crystalline silicon photovoltaic modules. Following the end of a solar plant's usable life, the amount of money generated by the solar panel is computed mathematically in this section. The BSDU 160 kW solar power plant is made up of 500 solar modules, each weighing 25.8 kg.

The total weight of 500 modules is 12,900 kg (500 x 25.8). (i.e., 12.9 ton). The recovery yield from the 160 kW solar PV plant is 100% for Al, 97 percent for Glass, 85 percent for Si, 78 percent for Cu, and plastics include the ethylene vinyl acetate sheet, which is not included in the calculation due to its fractional recovery compared to others. Table.5.6 indicates the composition of materials after recycling.

**Table 5.6** Material Composition after Recycling

S. No	Recycled & Recovered Materials	% Material Composition	Material Mass Recovered/12.9 ton (in ton)	Material Mass Recovered/12.9 tons (in Kg)
1	Al	17.5	2.257	2257
2	Glass	65.8	8.488	8488
3	Silicon	2.9	0.3741	374.1
4	Copper	1	0.129	129
5	Plastic	12.8	1.652	1652

**Table 5.7** Composite Material Costing after Recycling

S.No.	Recycled & Recovered Materials	Material Mass Recovered/12.9 tons (in Kg)	Market Price (Rs)/Kg	Prize of Recycled Material
1	Al	2257	145.12	327535
2	Glass	8488	9.07	76986
3	Silicon	374.1	126.98	47503
4	Copper	129	444.43	57276
5	Plastic	1652	95	156940
	Total Cost(B)			6,66,240

Each recovered element's market price is investigated, and the total amount recovered is projected to be about Rs 6,66,240 as mentioned in Table 5.7. As a consequence, a total of Rs 6,66,240 in gross profit was saved. However, only the cost of solar module recycling is considered; if the cost-benefit of materials recovered from dismantling the entire balance of system components (i.e., structure, connectors, cables, ACDB & DCDB boxes, Inverters, and so on) is also considered, the cost-benefit would be much greater. So, total plant saving during and after their life cycle = A+ B = 43,114,344 + 6,66,240 = RS 43,780,584

If these solar panels at their end of life are subjected to transportation to the suppliers for the end-life treatment, then the transportation expenses are also considered. If a vehicle requires 1 liter to travel 12 Km and per liter of petrol price is 108 then the expense of transportation to deposit the worn-out panels at the various Solar suppliers is shown in Table 5.8.

**Table 5.8** Transportation Expense of Solar Panels at their Eol to the Suppliers

<b>Supplier</b>	<b>Distance from BSDU in km</b>	<b>Petrol required in the liter</b>	<b>The expense of transportation in Rs</b>
Genus Innovation Limited, Sitapura Jaipur	39 Km	3.25	351
House of Solar, Kamla Marg, Jaipur	28 Km	2.33	251.64
Aardi Solar Energy Pvt. Ltd, Jagatpura, Jaipur	32 Km	2.66	287.28
Solar Maxx Solar Energy Solution, Subash Nagar, Jaipur	29 Km	2.41	260.28
Sun Power Solutions, Near City Centre, Sansar Chand Road, Jaipur	28 Km	2.33	251.64
SR Sunpower, Sodala Jaipur	25 Km	2.08	224.64
Ajit Solar Pvt Limited, Bagru, Jaipur	6 Km	0.5	54

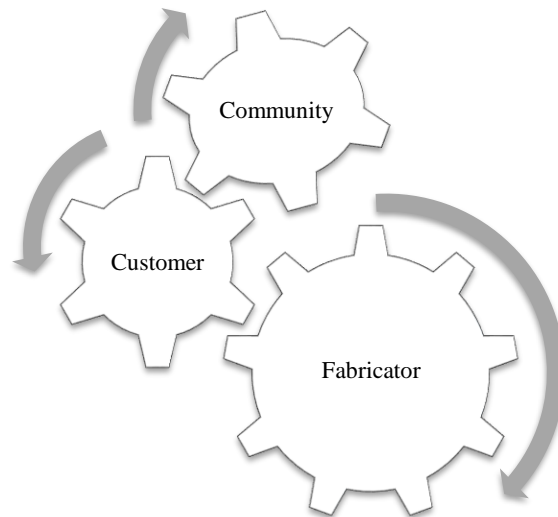
These expenses are to reduce the total profit output of the end-life treatment of the plant. The labor cost involved in the various stages of dismantling the panels at their end life, loading, and unloading of the waste is not taken under the economic analysis. The waste

so generated by the solar power plant under study can be further regulated by the policy implications as proposed here. Further, it should be mandatory for the suppliers to provide the end-life benefits within their initial plan of installation of solar power plants.

According to the current literature, improper disposal of discarded solar panels can have the following harmful effects on the environment and human health.

- a) Lead Leaching
- b) Cadmium Leaching
- c) Depletion of traditional resources, particularly glass and aluminum
- d) Rare metal losses, particularly silver, indium, gallium, and germanium

For the management of PV module waste, after the life cycle is attained, end-life liabilities are to be looked after. The end-life liabilities are represented in Fig. 5.7.



**Fig. 5.7** End Life Liabilities

1) Community:

Support of the community plays a critical role in the management of solar PV waste after the end of the life cycle. Encouragement by the community into waste management will hand out earnings to the local waste handling bodies of the particular area. For the managing of the waste proper compilation strategy is needed by a particular foundation body. The foundation body members for the compilation of the waste should be provided with wages. The provision of wages for the compilation

process will attract larger attention to this procedure to be done on a larger scale.

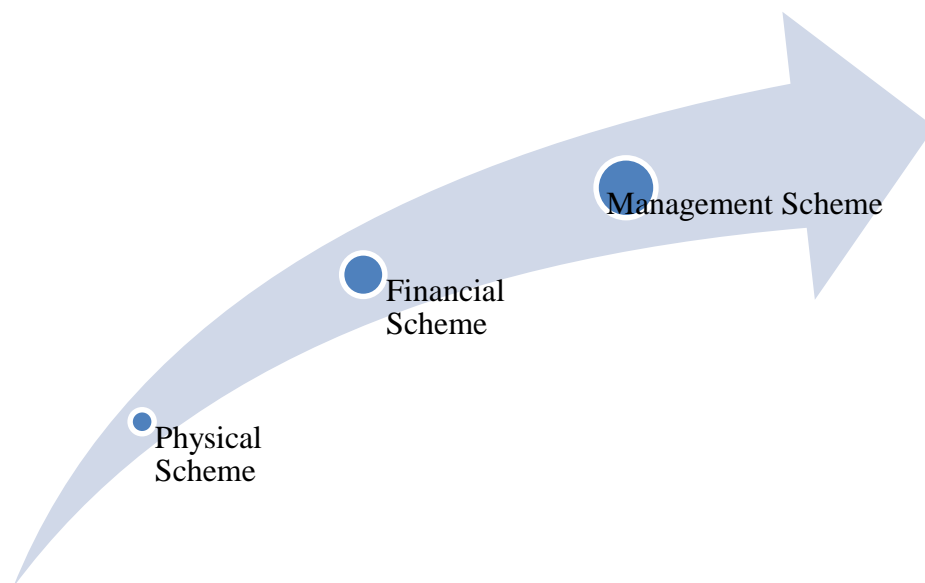
### 2) Customer:

Those who are utilizing the energy produced from the solar panels are responsible for the operation after their utilization is over. It depends altogether on the customer whether the panel is being disposed of for the treatment or it is simply thrown into land for its fate to meet. The customer can also hand over the solar panels to the waste collection centers for further supply to the recycling firms and can get budgetary returns. This will motivate the customer to earn likely benefits after the life cycle of the solar panels is over. Access to this practice is a substantial aspect of dealing with the waste management of solar photovoltaic modules across the world.

### 3) Fabricator:

The fabricator is responsible for the effects of solar panel waste on the environment. Through this one can wholly rely on the fabricator only for the compilation, treatment procedure, reprocessing steps, and disposing of steps too.

From the above-mentioned contributors i.e. community, customer, and fabricator the responsibility of proceedings of the whole management after their end life is over a management approach of all the varieties of the waste incorporates the capital costs consumed at each of the steps. The capital cost so utilized in the end-life management responsibility can be inferred in a coordinated manner as depicted underneath. Expenditure and funding are to be incorporated through various schemes to tackle the cost breakup for managing end life as shown in Fig.5.8.



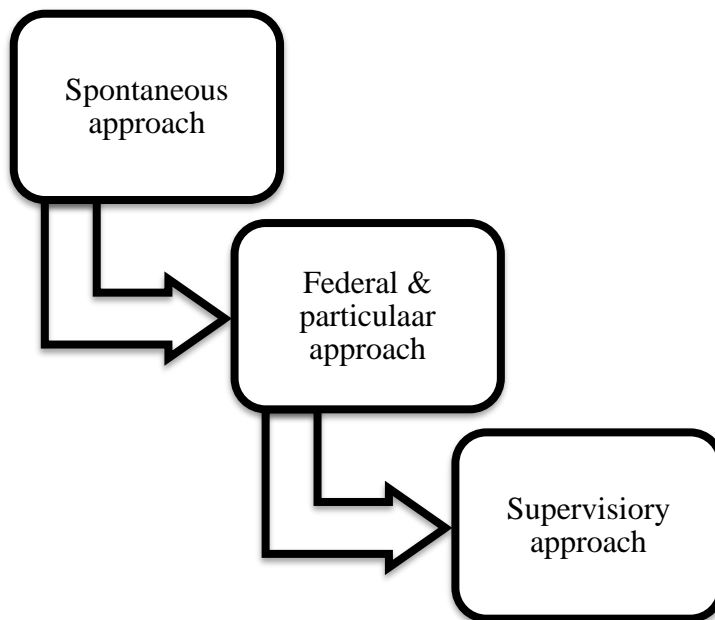
**Fig.5.8** Schemes to Tackle Cost Breakup for PV End Life Management

1. Physical Scheme: For this particular scheme independent waste propagation centers are to be taken care of and supplied to units where their primary treatment can be initiated. Later on, these waste materials are to be categorized into hazardous, non-hazardous, and inert materials. After this process, the different types of wastes are separated and then recovery of the materials is carried out. Recovery of elements used in solar panels is essential due to the lesser resource availability (Anctil & Fthenakis, 2013). In this scheme, hazardous materials are to be removed as they can hinder the process of the recovery of the materials during recycling. After the end of the procedure, the materials which cannot be recovered need to be taken care of by either disposing them or storing them in a safe environment (Tammaro et al., 2015). This particular scheme includes the whole computation in economic terms by considering the monetary values being spent at each step. Further, a concluding rate is added to the material in the recycling treatment.

2. Financial scheme: This deals with the all-over cost outputs of the material after the recycling process; it also includes the taxes on each scheme.

3. Management scheme: This particular system includes the management of the solar PV waste handling and the accountability of the finances which is to be implemented in the whole procedure.

Harmony should be established between the compilation of the PV waste, their reprocessing, and their recovery rate. Various accession steps need to be taken care of for effective waste management. A proper approach needs to be applied to the handling of PV waste as shown in Fig. 5.9.



**Fig. 5.9** Various Approaches to Tackle PV Waste.

1. Spontaneous approach:

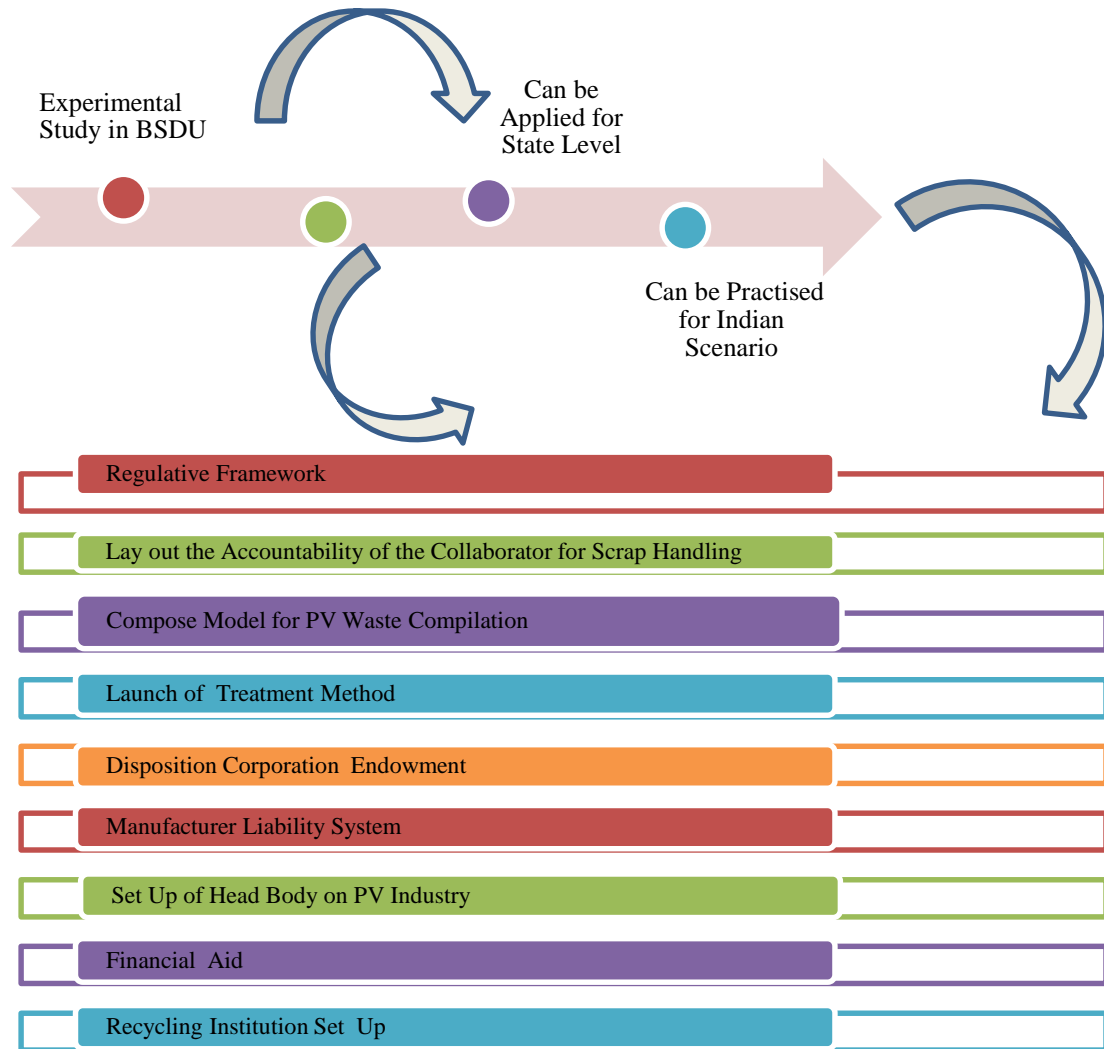
Some manufacturing firms have developed methods to check on their product's services to the environment. The such approach needs to be put together by the individual companies as discussed;

a) Candid management: Here the fabricator only is concerned with the recycling of the product. It's taken as an obligation by the manufacturing firm only. Recently First Solar has taken this initiative and it is taking the entire responsibility of the recycling of the solar panels manufactured by it.

b) Eventual management: In this approach, the fabricator indirectly regulates the collection centers for the compilation of waste and then sends it to the firms for further treatment.

2. Federal & particular approach:

In this method, a collaborative aspect is existing between both the company and the government. An autonomous program known as PV CYCLE was established in 2007 which deals with both the import of the PV waste into it and its uptake after its treatment has been processed. Through this program, finances will be provided by the manufacturer. This particular program was ingrained by the manufacturers who are prominent in this PV field. Cumulatively around 300 PV waste compilation hubs are resolved all over Europe.



**Fig.5.10** Outline of Proposed Solar PV Recycling for Indian Scenario

#### 5.4. Result & Discussion

Although solar photovoltaic technology is stated as a clean and environmentally amiable energy source but drawing near-end lifetime decommissioning is a paramount task, which further paves the way to transfer PV waste for the recycling process. With the flourishing solar PV installations recycling has also become an important segment to be dealt with. Henceforth it becomes the responsibility of each counterpart involved from raw material extraction to fabrication phase, and from operational phase to end life phase. The recycling strategy should involve a sustainable approach; it should take care of all the life phases. Solar photovoltaic waste material is also analyzed through reduction and reuse besides the recycling strategy.

The overall analysis of the 160 kW Grid connected rooftop solar photovoltaic plant reveals a beneficiary outcome. This includes major in terms of saving electricity bills as consumption from the grid increases the financial load on any institute. Here the complete reward is free electricity generated after energy payback time is attained. A further benefit is an added effect from the recycling of the Silicon panels at the end of life. However, the benefit discussed here is only from the recycling of the modules which is not greatly significant as crystalline Silicon modules are devoid of economic elements. This study focused on the module and its parts which are recovered significantly. Furthermore, the recycling policies as proposed in the report can also be applied to the BSDU Solar PV Plant to ascertain the truly sustainable development of the installed PV Plant on the BSDU Campus.