
3 End Life Cycle Cost-Benefit Analysis of 160 kW Grid-Integrated Solar Power Plant *BSDU Jaipur Campus*

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3.1 INTRODUCTION

Solar energy is a leading renewable energy source, and its long-term availability and immense potential have aided in the recovery of the world's developing environmental challenges. Photovoltaic (PV) materials have recently piqued the scientific community's interest in the development of solar cells with a direct bandgap and high

absorption co-efficient capabilities. The development of low-cost solar cell materials helps to lower the overall installation cost, making it more affordable to the average person.

The photovoltaic (PV) effect produces direct electricity from sunlight, where the terms light and electricity are connected to the terms photo and voltaic, respectively. The goal of a solar cell, which is a semiconductor light-sensitive device, is to create direct electricity from sunlight. In 1839, Edmund Becquerel was the first French scientist to notice the PV effect [1]. Still, it was only with the development of quantum theory and solid-state physics that it gained its unique character. In 1954, Chapin et al. [2] at Bell Laboratories discovered the first crystalline silicon solar cell with a 6% efficiency. Following that, researchers continued to make every effort to develop highly efficient solar PV materials [3–13].

The PV effect is a mechanism for producing direct electricity from sunlight, where the terms light and electricity are related to the terms photo and voltaic, respectively. The purpose of a solar cell, which is a semiconductor light-sensitive device, is to generate direct electricity from sunlight. In 1839, Edmund Becquerel was the first French scientist to notice the PV effect [1], but it was only with the development of quantum theory and solid-state physics that it gained its unique character. In 1954, Chapin et al. [2] at Bell Laboratories discovered the first crystalline silicon solar cell with a 6% efficiency. Following that, researchers continued to make every effort to develop highly efficient solar PV materials [3–13]. The United States introduced the first commercially available solar PV system in the 1950s as part of its space program. Although silicon-based PV cells currently account for the majority of the worldwide market, there are other semiconductor materials that, depending on their performance and cost, are offering reasonable competition to Si-based solar cells. The major types of Si and non-Si-based PV materials will be discussed in this chapter.

3.2 SOLAR PHOTOVOLTAIC CELL

When light is incident on a device known as a solar cell, a voltage generating phenomenon (PV effect) occurs. The device utilized in solar cell fabrication is a large-area semiconducting device that collects maximum solar energy from the solar spectrum and converts it into usable electrical energy.

The solar spectrum shows the strength of sunlight as it fluctuates throughout time. The relation between energy (E) and wavelength of radiation (λ) is:

$$E = \frac{hc}{\lambda} \quad (3.1)$$

where E is the photon energy, h is the Planck's constant, and c is the speed of light.

Figure 3.1 depicts the relationship between power (kWm) and wavelength (μm). Figure 3.1 shows that as the wavelength increases, the power decreases after the maximum power is reached.

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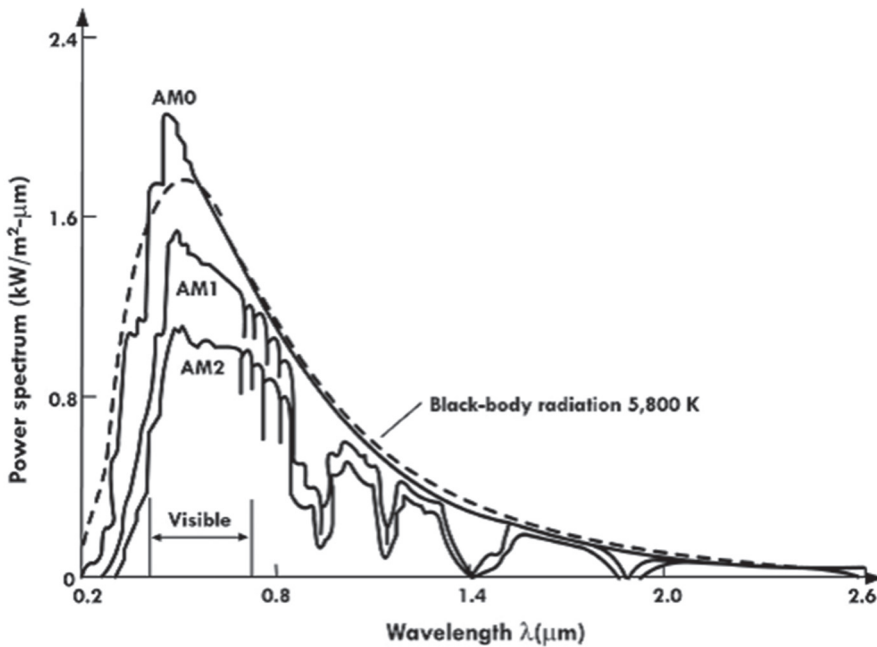


FIGURE 3.1 Solar spectrum associated with various air mass conditions. The spectrum AM₀ is related to outside the atmosphere, AM₁ is at the zenith and AM₂ is at an angle of 60°. (Taken from physics of semiconductor devices [22].)

The total intensity of incoming solar radiation can be calculated from the area under the curve [1,4].

3.2.1 PHOTOVOLTAIC ENERGY CONVERSION

As previously stated, PV energy conversion converts electromagnetic energy associated with ultraviolet, visible, and infrared wavelengths into direct electrical energy (either current or voltage) [5]. The PV energy conversion process is broken down into the following steps:

1. The first step in which absorption of light leads to the transition inside the material from the ground state to the excited state.
2. In the next step, negative and positive charge carriers are separated in opposite directions via an inbuilt electric field in the depletion region.
3. After this free charge carriers, i.e., negative charge and the charge carriers, are collected on cathode anode contact.

The cross-sectional perspective of a solar PV system is shown in Figure 3.2 to decrease reflectivity losses, and an anti-reflection coating is used.

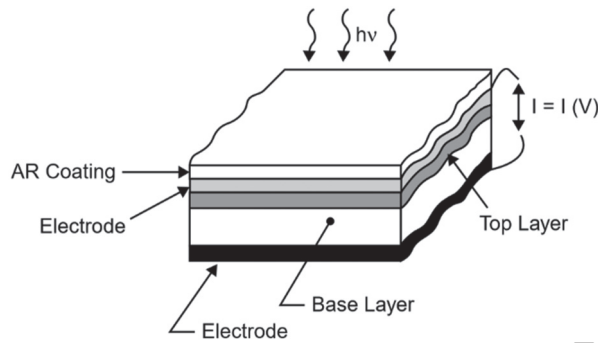


FIGURE 3.2 Cross-section of a typical solar cell.

3.2.2 IMPORTANT CHARACTERISTICS OF SOLAR CELLS

The electronic properties of a solar PV cell are explored through their equivalent circuit as shown in Figure 3.3.

Diodes are stacked parallel as a current source for an ideal solar cell. Shunt (R_{sh}) and series resistance (R_s) are introduced in the comparable circuit due to non-ideality of the device.

Total current can be calculated by subtracting photo-produced current from diode current under solar irradiation. Mathematically,

$$I = I_0(e^{qv/KT} - 1) - I_{ph} \quad (3.2)$$

To understand solar cell characteristics short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) are two important aspects. These two important situations are shown in Figures 3.4 and 3.5. The charges obtained by solar cell I_{SC} are allowed to move freely through the circuit and no build-up potential is present. Because no diode current is produced in this circumstance, the current generated by the solar cell is at its maximum.

In the case of V_{OC} charge builds up on each side of diode, cause diode current to flow. When the diode current and photo-produced current (I_{ph}) are equal, the solar cell is said to be in equilibrium. Silicon solar cells typically have a current of 1 mA and a voltage of 0.5 V. The IV characteristics of solar cells are given in Figure 3.6.

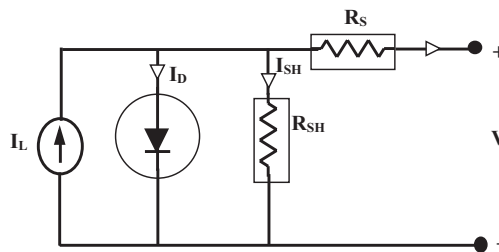


FIGURE 3.3 Equivalent circuit of the solar cell.

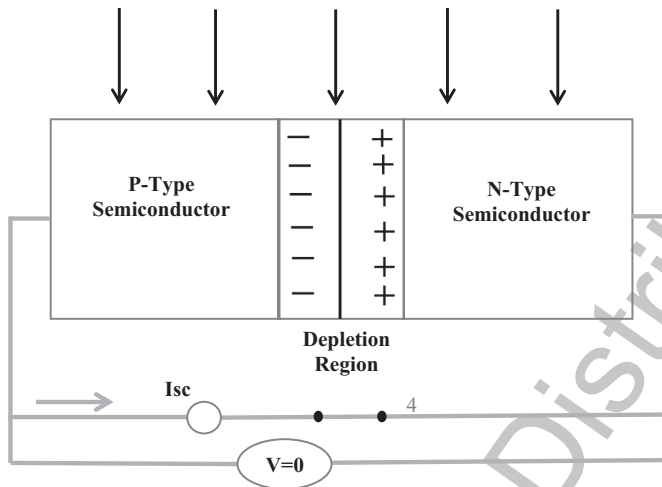


FIGURE 3.4 Short circuits current.

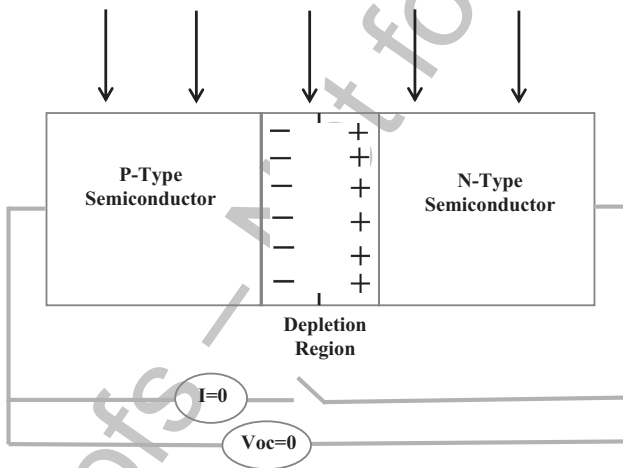


FIGURE 3.5 Open-circuit voltage.

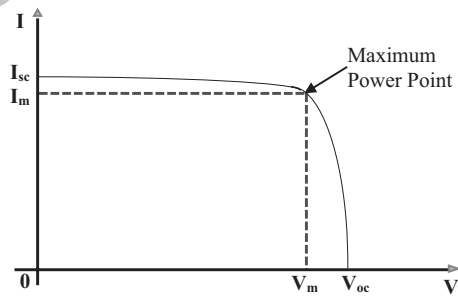


FIGURE 3.6 IV characteristics of the solar cell.

The output power of the solar cell is obtained by multiplying current and voltage. To check the quality of solar cells, we use the term fill factor (ff) which is defined as the ratio of maximum power ($P_{\max} = I_m * V_m$) to the product of the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}).

$$ff = \frac{I_m V_m}{I_{sc} V_{oc}} \quad (3.3)$$

For a perfect rectangular-shaped IV curve, the fill factor value is 1, but generally it ranges between 0.75 and 0.85. Further efficiency of solar cell is calculated as the ratio of output and input power:

$$\eta = \frac{P_{out}}{P_{in}} \quad (3.4)$$

3.2.3 SOLAR CELLS, MODULE, AND ARRAYS

To make a solar module, solar PV cells are joined in series and parallel. Individual cells are coupled in series and/or parallel to achieve high power levels. These modules are the core building blocks of a PV system. A solar PV array is formed when a number of solar PV modules are joined in series and parallel. A solar PV array can function as a full-fledged power plant. Figure 3.7 (a, b, c) [6,7] shows the whole construction of PV cells, PV modules, and PV array.

Solar energy is a game-changing technology that can help meet current and future global energy demands. The Indian government is taking considerable measures to combat global warming and non-renewable pollutants [14–21]. Solar energy has emerged as a potential option for fulfilling future energy demands [21].

On the roof of Bhartiya Skill Development University Jaipur a 160 KW grid-integrated solar PV plant has been installed. BSDU is India's first skill-based university located in Mahindra World City, Jaipur, Rajasthan. Even if the goal is to provide

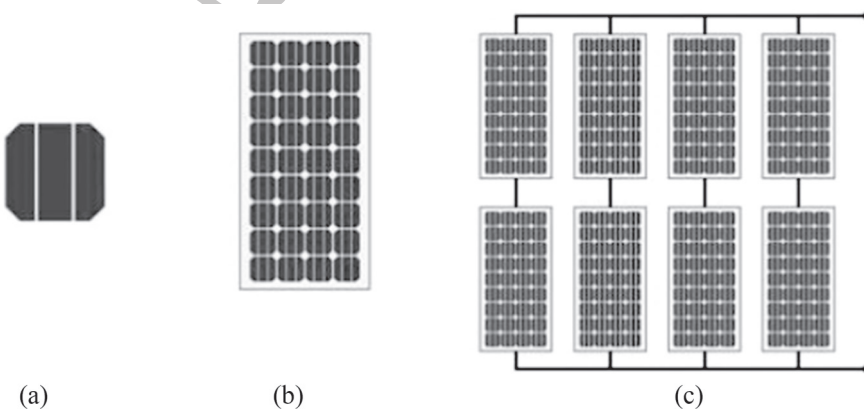


FIGURE 3.7 (a) Solar PV cell. (b) Solar PV module. (c) Solar PV array.

electricity to every corner of India, the electricity cost still varies in Rajasthan. Using and installing grid-connected solar PV systems can solve this issue. It creates surplus power rather than meeting load requirements. When the same grid (on-grid) generates less power than the load demand, it takes the surplus electricity from the grid to meet the load. To promote easy recycling and eliminate dangerous components, manufacturers should be held accountable for end-of-life standards. This will aid in the development of an autonomous and sustainable society in the face of the fossil-fuel crisis.

3.3 METHODOLOGY

In April 2017, 160KW on-grid rooftop solar PV plant was installed at BSDU Jaipur campus. The site consists of 500 numbers of Anchor Panasonic crystalline silicon panels of 320 Wp rating. The solar panel, inverter, battery, mount structure, and storage batteries are all part of this system. The panels at the rooftop grid-connected plant are fixed at a 0° azimuth angle and a 26° inclination leaning south. Panels are installed in a shade-free location during installation. Anchor Panasonic crystalline silicon panels rated at 320 Wp are used. The mechanical characteristics of the planned solar plant's solar panels are listed in Table 3.1. These panels are resistant to elements such as salt, moisture, dust, rust, and shadow.

On-grid solar PV system designing of BSDU 160kW on-grid solar power plant has been performed. For string sizing inverter datasheet and solar PV module datasheet has been utilized. For proper string sizing approximate maximum (i.e., 45°C) and minimum (10°C) BSDU Jaipur site location temperature has been also taken into account.

TABLE 3.1
Technical Datasheet of ABB Make 50kW on Grid Inverter

Absolute maximum DC input voltage (V_{max})	1,000V
Start-up DC input voltage (V_{start})	300–500V (default 360)
Rated DC input voltage V_{der}	715 rated DC input V_{dc}
Rated DC input power P_{der}	51,250 W
Number of independent MPPT	1
MPPT input DC voltage range	520–800 V_{dc}
Maximum DC input current (I_{demax})	100 A
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	50,000W
Maximum AC output power	50,000W
AC voltage range	422–528V
Maximum AC output current (I_{acmax})	61 A
Rated output frequency (f_r)	50Hz

TABLE 3.2**Technical Datasheet of 320 Watt Anchor Panasonic Make Solar Panel**

STC	AE7P320VB4B	AE7P315VB4B	AE7P310VB4B
Maximum power at STC (P_{max})	320 W	315 W	310 W
Optimum operating voltage (V_{mp})	37.1 V	36.8 V	36.5 V
Optimum operating current (I_{mp})	8.63 A	8.56 A	8.50 A
Open-circuit voltage (V_{oc})	45.6 V	45.1 V	44.9 V
Short-circuit current (I_{sc})	9.14 A	9.02 A	8.96 A
Module efficiency	16.5%	16.2%	16.0%
Operating module temperature		-40°C to +85°C	
Maximum system voltage		1,000 V DC	
Module weight		25.8 kg	
Maximum series fuse rating		20 A	
Temperature coefficient of V_{oc}		0.33%/°C	

There are a total of 500 320-Watt Anchor Panasonic make solar PV modules and three 50kW, 3 ϕ , 400V ABB make inverters are used to construct 160 kWp grid-connected solar PV system. The technical datasheet of solar PV modules and inverters are shown in Tables 3.1 and 3.2, respectively.

Designing Steps of 160kW BSDU Solar PV Plant:**Estimate Required Number of PV Modules**

PV modules with various power ratings (e.g., 3 Wp, 6 Wp, ..., 100 Wp, 200 Wp, 300 Wp) are available on the market.

We utilize Panasonic Anchor make 320 Wp PV modules that are readily accessible on the market. For a 160kW solar PV system, the total number of PV modules required would be:

$$= \frac{160 \text{ kW}}{320 \text{ Wp}} = 160 \text{ kW}/320 \text{ Wp} = 500 \text{ modules}$$

Hence, 500 number of solar PV modules will be required for a 160kW plant.

Effect of Temperature on Voltage

Temperature coefficient of voltage = -0.33%/°C

Voltage rise in winter = $V_{oc} \times (-0.0033)$ (STC temperature – Minimum temperature)

$$= 45.6 \times 0.0033 (25 - 15) = 1.50 \text{ V}$$

Total voltage in winter/Maximum voltage = $V_{oc} + 1.50 \text{ V} = 45.6 + 1.50 = 47.1 \text{ V}$

Voltage fall in summer = $V_{oc} \times (0.0033)$ (STC temperature – Minimum temperature)

$$= 45.6 \times 0.0033 (25 - 45) = -3.00 \text{ V}$$

Total voltage in summer/Minimum voltage = $V_{oc} - 3.00 \text{ V} = 45.6 - 3.00 = 42.6 \text{ V}$

Maximum and Minimum Number of Modules in a String

$$\text{Minimum modules in a string} = \frac{\text{Inverter MPPT lower start voltage}}{\text{PV Module } V_{mp}}$$

$$\frac{360}{47.1} = 7.64 = 8 \text{ modules}$$

$$\text{Maximum modules in a string} = \frac{\text{Maximum MPPT DC input voltage of inverter}}{\text{PV Module } V_{mp}}$$

$$= \frac{800}{47.1} = 16.98 = 17 \text{ modules}$$

Number of strings in parallel = Total number of PV modules in the system /
 Number of modules in a string = $\frac{500}{17} = 29.41 = 30$ parallel strings (by considering
 maximum modules in the string) = 29.41 = 30 parallel strings (by considering maxi-
 mum modules in the string)

Maximum and Minimum Number of Modules in a String

Since a maximum of 17 modules are used to form a series string, their output voltage is

$$= 17 \times V_{oc}$$

$= 17 \times 47.1 = 800 < 800 \text{ V}$ (i.e., equal to maximum MPPT DC input voltage of
 inverter – accepted)

Hence, 30 parallel strings of 17 modules are possible. Here we are using three
 ABB make, 50 kW, 3-phase, 440 V rating inverters.

AU: Can this be 'inverter accepted' as used in the equation in page 52?



$$\text{Total number of parallel string per inverter} = \frac{\text{Maximum number of parallel strings}}{\text{Number of inverters}}$$

$$= \frac{30}{3} = 10 \text{ parallel strings per inverter (approximately)}$$

So we can connect a maximum of 10 number of parallel strings per inverter

Total output current of the parallel string

$$= \text{No. of parallel string} \times \text{Maximum current of a module}$$

$$= 10 \times 9.14 = 91.4 < 100 \text{ A (Maximum DC input current of inverter accepted)}$$

The interconnection diagram of BSDU 160 kW solar power plant is shown in Figure 3.8.

Results Discussion

Table 3.3 shows that the total unit generation of the 160 kW solar power plant on the BSDU Jaipur campus was 245,876 kWh from April 2018 to March 2019. The cost per unit electricity consumption is Rs. 8.35.

Total savings from plant (April 2018 to March 2019) = $245,876 \times 8.35 = \text{Rs. } 2,053,064$

The materials and installation cost of the BSDU 160 kW solar PV plant is around Rs. 8,467,500, as shown in Table 3.4.

The plant has a 25-year life cycle. We can compute the plant's energy payback period to see how long it will take for the plant to provide free electricity.

$$\text{Energy payback Period} = \frac{\text{Total cost of solar power plant}}{\text{yearly unit cost generation by solar plant}} = \frac{8,467,500}{2,053,064} = 4.12 \text{ years}$$

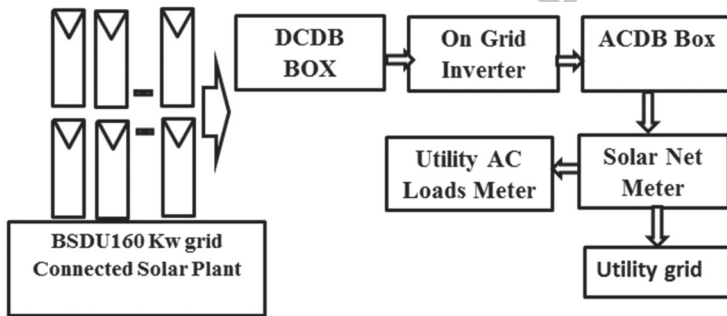


FIGURE 3.8 BSDU 160 kW solar power plant.

TABLE 3.3
Main Solar Meter Reading

Month	Date of Reading	Total kWh
April	1-04-2018	24,240
May	1-05-2018	23,500
June	1-06-2018	24,144
July	1-07-2018	21,020
August	1-08-2018	16,856
September	1-09-2018	15,652
October	1-10-2018	17,364
November	1-11-2018	22,108
December	1-12-2019	19,344
January	1-01-2019	20,188
February	1-02-2019	20,140
March	1-03-2019	21,320
Total kWh		245,876
Monthly average kWh		20,489

TABLE 3.4
BSDU 160kW Solar PV Plant Materials & Installation Cost

S. No.	Description	Amount (INR)	Rate Per/Watt
Materials	Solar PV modules	8,136,000	54.24
	Inverters		
	MS galvanized structure		
	Balance of system components: AC/DC wires, light arrestor, PVC, conduits, earthing		
Installation and commissioning charges	Installation and commissioning charges	3,31,500	2.21
Total cost		8,4,67,500	

Energy payback Period = Total cost of solar power plant/yearly unit cost generation by solar plant = $8,467,500/2,053,064 = 4.12$ years

Since the life cycle of a plant is around 25, years, and after 4.12 years the plant will generate free electricity for approximately the next 21 years.

After 4.12 years, for the next 21 years electricity generated by solar plants is almost free.

Total free electricity produced by solar plant (A) = $21 \times 2,053,064 = \text{Rs. } 43,114,344$

End Life Solar PV Module Cost Analysis

When the solar panels on the 160kW 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 [23]. 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 [24]. D'Adamo and colleagues [25] estimated the mass fraction of tons of crystalline silicon 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 160kW solar power plant is made up of 500 number of solar modules, each weighing 25.8 kg.

The total weight of 500 modules is 12,900 kg (500×25.8) (i.e., 12.9 ton). The recovery yield from the 160kW solar PV plant is 100% for Al, 97% for glass, 85% for Si, 78% for Cu, and for plastics include the ethylene vinyl acetate sheet, which is not included in the calculation due to its fractional recovery compared to others [26]. Table 3.5 shows the composition of materials after recycling.

Market price of each recovered element is investigated [14], and it is found that the total recovered amount is around Rs. 666,240 as mentioned in Table 3.6.

As a consequence, a total of Rs. 666,240 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.

TABLE 3.5
Material Composition after Recycling

S. No.	Recycled & Recovered Materials	% Material Composition	Material Mass Recovered/12.9 Ton (in Ton)	Material Mass Recovered/12.9 Ton (in kg)
1	Al	17.5	2.257	2,257
2	Glass	65.8	8.488	8,488
3	Silicon	2.9	0.3741	374.1
4	Copper	1	0.129	129
5	Plastic	12.8	1.652	1,652

TABLE 3.6
Composite Material Costing after Recycling

S. No.	Recycled & Recovered Materials	Material Mass Recovered/109.37 Ton (in kg)	Market Price (Rs.)/kg	Price of Recycled Material
1	Al	2,257	145.12	327,535
2	Glass	8,488	9.07	76,986
3	Silicon	374.1	126.98	47,503
4	Copper	129	444.43	57,276
5	Plastic	1,652	95	156,940
	Total Cost(B)			6,66,240

So, total plant saving during and after their life cycle = $A + B = 43,114,344 + 666,240 = \text{Rs. } 43,780,584$.

3.4 CONCLUSION

The current research looks at the design and lifecycle assessment of a 160 kW rooftop solar PV system. This includes significant power bill reductions, as system usage increases any institution's financial burden. The overall savings from a 160 kW BSDU solar PV plant during its life cycle and beyond its end-of-life cycle is Rs. 43,780,584, which is a significant amount of money saved in terms of electricity costs. After the energy recovery period is met, the complete reward is the free electricity generation.

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