

## Chapter 7

### Design, Techno-economics and Environmental assessment of 500 kWp On-grid rooftop PV plant

#### 7.1. Introduction

Solar photovoltaic technology has emerged as the fastest growing among various renewable energy technologies. In this work a simplified and real time design procedure followed by techno-economics and environmental assessment of a 500 kWp rooftop grid connected system is provided. The design results are based on the site meteorological data and datasheet values of connected components. A detailed energy metric analysis is presented which indicates EPBT to be 5.96 years and capacity utilization factor of 16.93%. Discounted payback period is found to be varying between 6.7 years to 17.4 years as nominal discount rates changes from 6% to 15%. Project NPV varies from ₹68,567,443.60 to ₹4,639,553.94 with same variation in discount rates. Finally, a comparative life cycle assessment is presented using data from GaBi (Indian extension database). Based on the discussion, the proposed system is found to be feasible and offers significant environmental and financial benefits.

Based on the last census India has a population of 1.3 billion and is set to become the most populous country by the end of this decade. It has also maintained a steady economic growth rate in the last decade. The sustained economic growth coupled with its large population has put significant stress on its energy resources. In the past decades, the collective energy demand has grown steadily across all sectors. However, the per capita consumption is still 30% of the world average. Such disparity may be accounted for by the fact that India's economy is itself highly diverse. Each sector viz. agriculture, large

scale industries, MSMEs, and variety of services have their constraints and growth trajectory. While government has been committed towards its obligation to UNFCCC under the INDC, any policy change in the energy sector has to be discussed with all stakeholders. In the last decade, there has been significant progress towards reducing the dependencies on conventional power plants with the launch of NAPCC in 2008. Solar power has been at the forefront of NAPCC with the phased implementation of the National Solar Mission. Studies aimed at assessing India's renewable energy potential have pointed to the regional variation and various technological constraints. India being a tropical nation acquires abundant solar radiation with GHI ranges between 3.9 to 6.0 kWh/m<sup>2</sup>/day. The maximum potential for solar PV ranges from 5200-6000 GW [134]. However, the true prospects is restricted by land availability, regional landscape, and annual variation in the solar irradiance. Such factor along with weak finances of India's DISCOMS have made a uniform implementation of solar policy a challenge for the government.

Solar power has an inherent advantage over other RE sources as solar radiation is not only a source of electricity generation based on the PV effect but also a significant source of thermal energy. The PV industry has been at the forefront in the growth of the solar power sector on the account of rapid technological advancement and various governmental policies. In a recent study done by Irena shows that the solar PV sector has shown a CAGR of 43% since 2000. In addition to that solar thermal sectors have also shown rapid developments over the years [135]. In recent years several studies have been conducted to integrate solar PV and thermal technology. It has been shown that such integrated technologies have the potential to improve the overall system performance [2]. PV/T hybrid systems are shown to have significant potential for HVAC applications [136,137].

The solar panels are the basic operating blocks of solar PV technology and hence their performance directly impacts the overall system performance. The inherent sensitivity to PV modules makes it necessary to carry out a comprehensive system modeling to accurately predict the energy generation potential of the system [138]. Modeling requires a large number of input data including weather, environmental conditions as well as technical parameters related to the system under study. Can and Ickilli developed a method to estimate certain input parameters from the module datasheet values [139]. Bellia et al. carried out detailed modeling of PV Module using [140]. Similar studies were examined to assess the sensitivity of PV module performance on varying environmental conditions. Case studies were accomplished to investigate the functioning of PV system with battery storage under intermittent solar radiation [141]. A novel method to investigate the effects of dust on the efficiency of grid-connected solar power systems in Oman was developed in a previous work [142].

RE projects generally have high CAPEX which makes it unviable for implementation unless policy support is provided [143]. The policy support is given in terms of viability gap funding, priority sector lending, accelerated depreciation benefits, awarding RE certificates, and long term contracts in terms of PPA [144]. Despite such policy support, adoption of a new technology often suffers from lack of confidence from end users as well as from potential investors. This makes it essential to conduct feasibility study along with a complete techno-economic assessment for any new solar power project. A comprehensive study was carried out using a techno-economic feasibility study to assess the potential of grid-connected PV system in Oman using MATLAB software [145]. A methodology for design and assessment of a 336 kWp Off-grid solar power plant was presented in a study [146]. Literature survey shows simulation software are widely used

for performance assessment of solar PV system [147]. Imam et al. analysed the feasibility of a RSP system for domestic buildings in Jeddah using SAM [148]. A. N. Akpolat et al. carried out a simulation study of 84.75 kWp Rooftop solar PV system using PV Sol in Turkey [149]. V. Boddapati and S. A. Daniel carried out a performance evaluation of 50MW solar farm in Kurnool India [150] wherein, a comparative assessment of fixed tilt and single axis tracking system was studied.

Solar powered technologies have an inherent advantage of being environment friendly as its operation is completely emission free. However, to correctly assess its environmental benefits a comprehensive environmental impact assessment is essential. Such a study invariably involves an estimation of lifetime energy demand followed by an energy metric analysis. A. Tiwari et al. presented a detailed energy metric analysis for a ground standing PV/T hybrid system in Delhi [151]. R. Sharma and G. Tiwari had carried out a complete life cycle assessment of an independent solar system and concluded that rooftop mounted systems have comparatively better performance than ground mounted systems[152]. Such studies can be used as a benchmarking tool to assess emerging PV technologies.

In the current study a techno-economic assessment of a rooftop grid connected Solar system is presented. An attempt has been made to provide systematic design procedures along with a life cycle assessment and project feasibility study. Finally, a comparative study between different energy sources has been done based on LCA data.

### 7.1.1. Site description and details

The proposed solar plant in the case study is installed in CSIR- National Metallurgical Laboratory, Jamshedpur city in India. The details of the site are given in **Figure 7.1** and **Table 7.1**.

Table 7.1- Site details

Sl. No.	Description	Details
1.	Latitude/Longitude	22.775572/86.205519
2.	State/District/	Jharkhand/ Purbi Singhbhum
3.	Day Length (Min/Max)	10.60/13.40 hours
4.	Avg. Temp. (Min/Max)	20.1°C/31.6 °C
Source: NIWE (MNRE) Statistics		

Average daily solar insolation (kWh/m<sup>2</sup>) in different months throughout the year 2021 and 2022 received at the proposed site is listed in **Table 7.2**. It was observed that average solar insolation for the years 2021, 2022 is 4.40 kWh/m<sup>2</sup> and 4.14 kWh/m<sup>2</sup> respectively.

Table 7.2- Annual variation of solar insolation for site location

Month	Solar Insolation (kWh/m <sup>2</sup> )	
	2021	2022
January	3.29	2.65
February	4.11	4.04
March	5.10	4.19
April	6.17	5.87
May	5.77	5.87
June	4.57	5.17
July	3.48	3.39

August	5.32	4.45
September	4.27	3.97
October	4.42	3.90
November	3.70	3.57
December	2.65	2.65
<i>Average</i>	<i>4.40</i>	<i>4.14</i>



Figure 7.1- Site for proposed RTGS plant ( Suncalc: Solar data for selected location)

## 7.2. Load survey of building

Electrical connected loads of the building are segregated as per load and demand factor. Process and utility loads of the building are identified and tabulated for calculation of net energy requirement. It is found that energy demand is highest from 08:00 AM to 06:00 PM and sufficiently low from 06:00 PM to 08:00 AM. Details of connected loads in the industrial establishment are provided in **Table 7.3** and **Table 7.4**. As the peak load is

observed during day time, it was evident that investing in the energy accumulator system for the plant is not viable. As an outcome, on-grid roof top solar PV system is proposed to feed the utility loads with an option to feedback the unutilized power to the local grid. Process loads connected with existing building electrical system indicates the intermittent nature of the operation and percentage loading is considered for ascertaining the total energy demand. Total kW load of the building is calculated as 662 kW with the net daily energy requirement of 5244 kWh. Considering the net active operation time of 8 hours from the solar plant, effective energy requirement from the plant is calculated to be 1748 kWh as calculated in **Table 7.5**. This value is chosen as the base parameter for designing the plant. This solar plant is connected on to grid for effective utilization of generated power according to variations in the connected load.

Table 7.3- Load survey for technical block (A)

Sl. No.	Type of Load	Total kW Rating (Connected)	Running Load	Total kW Rating	Hours of operation	Energy Demand (kWh)
1.	Computer	16.80	50%	8.40	6.0	50.40
2.	Printer	2.00	15%	0.30	0.5	0.15
3.	Lighting	10.80	50%	5.40	6.0	32.40
4.	Motors	312.00	30%	93.60	1.0	93.60
5.	Furnaces	168.10	15%	25.22	4.0	100.86
6.	Testing equipment	60.30	10%	6.03	1.0	6.03
7.	Furnace Transformers	119.00	4%	4.76	4.0	19.04

8.	Welding sets	34.00	30%	10.20	4.0	40.80
9.	Stabilizers	21.50	50%	10.75	6.0	64.50
10.	UPS	64.00	25%	16.00	6.0	96.00
11.	Servers	16.10	25%	4.03	6.0	24.15
12.	Air conditioners	37.00	50%	18.50	8.0	148.00
<i>Daily Energy Demand</i>						675.93

Table 7.4- Load survey for technical block (B)

Sl. No.	Type of Load	Total kW (Connected)	Running Load	Total kW Rating	Hours Of Operation	Energy Demand (kWh)
1.	Computer	81.00	50%	40.50	6.0	243.00
2.	Printer	27.00	15%	4.05	0.5	2.03
3.	Lighting	75.12	50%	37.56	4.0	150.24
4.	Motors	25.00	30%	7.50	4.0	30.00
5.	Furnaces	137.50	15%	20.63	4.0	82.50
6.	Testing equipment	59.50	10%	5.95	3.0	17.85
7.	Stabilizers	30.00	25%	7.50	4.0	30.00
8.	UPS	20.00	25%	5.00	6.0	30.00
9.	Rectifiers	43.00	25%	10.75	2.0	21.50
10.	Air conditioners	65.00	50%	32.50	8.0	260.00

<i>Daily Energy Demand</i>	867.00
----------------------------	--------

Table 7.5- Estimated load and energy requirements

Sl. No.	Description	Technical Block (A)	Technical Block (B)	Pilot Plant (A)	Pilot Plant (B)	East block	Total
1.	Effective	203	171	89	31	168	662
2.	Energy	675	867	421	105	3176	5244
<i>Energy requirement for 8 hours operation in kWh</i>							1748

### 7.3. Key design aspects of PV plant

The on-grid PV system is considered for the site and an analytical method was adopted to design the PV system. For designing the PV system, load survey of the utility provides the gross estimated energy requirement. Solar irradiance analysis of the location provides an insight for the type of solar panel selection for the designed plant. Selection type and the number of solar panel can decide the plant capacity. Inverter design and the selection was made based on the topology of the array and string layout. The detail design basis of the plant is discussed below.

#### 7.3.1. Panel generation factor

Panel generation factor plays a principle role in PV system design. Geographical irradiance data of a specific site will help in computing this parameter. Solar irradiance data for the past 10 years obtained from ISRO's solar calculator is mentioned in **Table 7.6** to find the daily solar radiation in kWh/m<sup>2</sup>. This parameter is the measure for the amount of electrical energy generated per each Wp rating of the PV system.

Table 7.6- Solar irradiance data for Jamshedpur

Month	Solar Insolation (2009-2019)	
	(kWh/m <sup>2</sup> )	
	Monthly Total	Daily Average
January	97	3.13
February	117	4.18
March	155	5.00
April	190	6.33
May	181	5.84
June	144	4.80
July	122	3.94
August	151	4.87
September	129	4.30
October	139	4.48
November	108	3.60
December	85	2.74

Panel Generation factor

$$\begin{aligned}
 &= \frac{\text{Daily solar Radiation}}{\text{Standard Test Condition Irradiance of selected PV Panel}} \\
 &= \frac{4.43 \times 1000}{1000} = 4.43 \dots\dots\dots(1)
 \end{aligned}$$

7.3.2. Estimated energy requirement

Detailed load survey of utility loads in the building gives the gross energy requirement. For calculating net estimated energy requirement of plant, loss compensation factor was also considered. Loss compensation factor was determined with the help of PV Syst software and net system losses are found to be 21.4% of the array nominal output energy generation. Energy generation from PV plant is considered to feed peak loads for 8 hours' duration during day time and hence the proposed share of the solar PV plant is found to be 1836 kWh with 5% margin factor. By considering the system drops as shown in **Figure 7.2**, the system loss factor is chosen as 1.214.

Energy Requirement from PV system

$$= \text{Daily Energy Demand} * \text{Loss Compensation factor}$$

$$= 1836 * 1.214 = 2228 \text{ kWh} \dots \dots \dots (2)$$

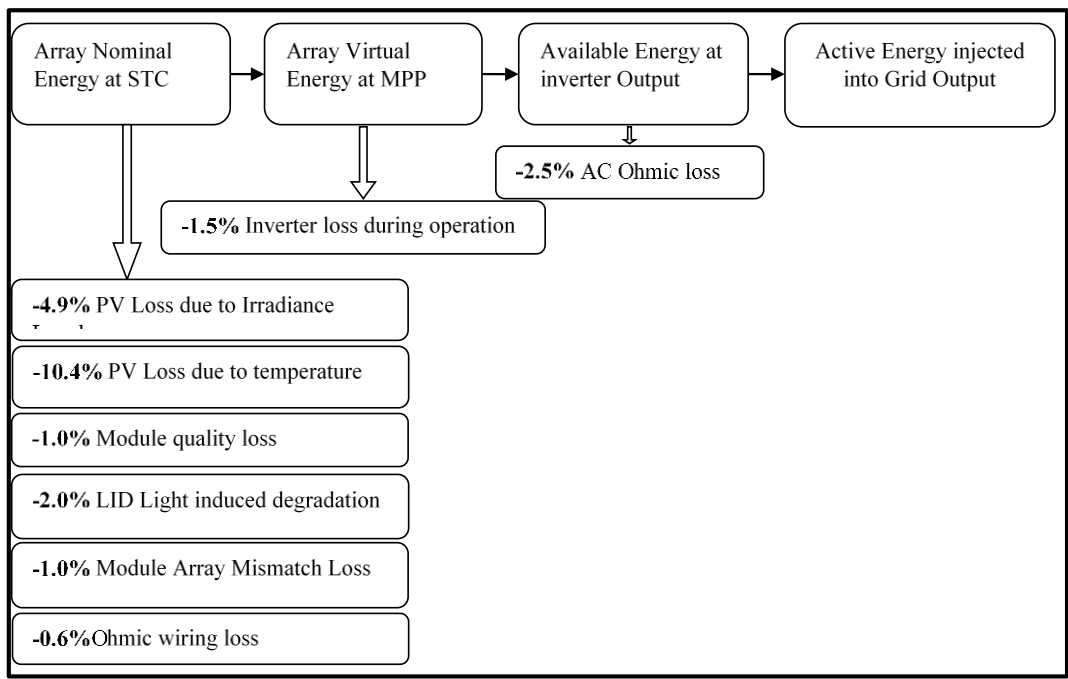


Figure 7.2- System loss diagram

### 7.3.3. Determination of plant watt peak rating

Plant watt peak rating decides the plant sizing. Planned energy demand for the utility loads along with panel generation factor was considered for determining this factor.

$$\begin{aligned} \text{Watt peak Rating} &= \frac{\text{Plant Energy Demand}}{\text{Panel generation factor}} = \frac{2228}{4.41} = \\ &= 505 \text{ kWp} \dots \dots \dots (3) \end{aligned}$$

### 7.3.4. PV module selection

PV module selection along with the number of modules connected in the array defines the energy generated at output terminals. Total number of PV modules used in a particular plant can be calculated as-

$$\begin{aligned} \text{Total No. of modules} &= \frac{\text{Plant Watt peak Rating}}{\text{Wp rating of each module}} = \frac{505 \times 1000}{325} = \\ &1550 \dots \dots \dots (4) \end{aligned}$$

Rating of each selected PV module is 325 Wp obtained from the technical datasheet. Polycrystalline PV modules with the specifications mentioned in **Table 7.7** are selected for the mounting. Technical parameters along with general arrangement details were analyzed and selected to match the suitability for the designed plant.

Installation of panels are designated as per building location and was planned according to the free floor space area of the roof. For East block with 55.25 kWp rating, 170 numbers of modules were selected.

$$\text{Total No. of modules} = \frac{\text{Plant watt peak rating}}{\text{Wp rating of each module}} = 55.25 * \frac{1000}{325} =$$

170 modules ..... (5)

Table 7.7- Solar PV module technical data (Solar Impex), STC 1000W/m<sup>2</sup>, Spectrum 1.5, Cell temperature 25°C

Parameter	Units	At STC
Module Type	ENERGIA 325 Wp Polycrystalline PV module	
Total No. of Cells	Nos.	72
Maximum Power	W	325
Maximum Power Voltage V <sub>max</sub>	V	37.3
Maximum Power Current I <sub>max</sub>	Amp	8.42
Open Circuit Voltage V <sub>oc</sub>	V	46
Short Circuit Current I <sub>sc</sub>	Amp	9.2
Module Efficiency	%	16.75
Cells configuration		12X6
Dimensions (l X w X h)	mm	1960X990X42
Module Weight (approx.)	kg	23
Frame Material		Anodized Aluminum

### 7.3.5. Inverter selection

Based on the available rooftop area and energy requirement, the plant area was segregated into eight different zones. Each individual zone is having a specified set of strings from respective solar arrays and connected forward to individual inverter unit. Selection and sizing of a specific inverter unit depend on the number of connected strings and the amount of modules per each string. In the detailing given blow, eastern block zone is considered as an example. From the available roof area of the east block, finalized array layout design gives the 55.25 kWp. 10% safety factor of was considered in the sizing of Inverter.

Maximum input DC power to inverter for east block =  $55.25 * 1.1 =$

60.775 kWp ... ..(6)

MPI-50A Inverter model of Delta was selected for the east block zone having maximum DC input power of 62.5 kWp and designed for a maximum input voltage of 1000 V with rated output current of 76 A. Technical details of selected Inverter model is given in

#### Table 7.8.

Table 7.8- Solar inverter technical details (Delta), for east block zone

Parameter	Units	At STC
Model	<b>RPI-M50A</b>	
Max. DC Power Input	kWp	62.5
Max. Input Voltage	V	1000
Total Input Current	Amp	100
Rated Output Power	kVA	50
Rated Output current	Amp	76

Nominal AC Voltage	Voltage	3Ph, 400
Nominal Frequency	Hz	50
Power Factor at Rated Power		Unity
Maximum Efficiency		98.6
Dimensions (h X w X d)	mm	740X612X278
Weight (approx.)	kg	70
Operating Temperature Range	°C	-25 to +60

**7.3.6. Module circuit design**

Module circuit design includes determining the array structure of the PV modules for a given output rating. Broadly, it estimates the amount of PV modules to be in series in an array and the number of arrays in parallel to obtain the desired output characteristics. Size of an individual array depends on the voltage ratings of inverter and of each PV module.

$$\begin{aligned} \text{Size of an array} &= \frac{\text{Maximum Open Circuit Voltage of Inverter}}{\text{Open Circuit Voltage of each PV Module}} \\ &= \frac{1000}{46} = 21.73 \approx \\ &22 \text{ modules} \dots \dots \dots (7) \end{aligned}$$

Maximum voltage input to the inverter

$$\begin{aligned} &= \text{Maximum Power Voltage (Vmax)} * \text{No. of Modules in series} \\ &= 37.30 * 22 = \\ &820.6 \text{ V} \dots \dots \dots (8) \end{aligned}$$

$$\begin{aligned} \text{Total number of arrays} &= \frac{\text{Total number of Modules}}{\text{Number modules in each array}} = \frac{154}{22} = \\ &= 7 \text{ Arrays} \dots \dots \dots (9) \end{aligned}$$

From the analysis of the east block, it may be observed that PV panels are mounted in seven different number of parallel-connected arrays, with each individual array housing the 22 numbers of series-connected modules.

#### **7.4. Energy metric analysis for PV plant installation**

In order to effectively study the environmental impact of a solar PV system and to identify the economic viability of projects, it is essential to carry out a comprehensive energy metric analysis for such systems. Such an analysis invariably aims to find out certain key plant characteristics include the life cycle conversion efficiency, the energy payback period, and the energy production factor and capacity utilization factor. These factors are important indicators for solar system performance. Energy metric analysis is the first step towards the study of the life cycle assessment of a solar PV plant. This analysis will be carried out to know the quantity of energy consumption during the different various life cycle stages starting from manufacturing to point of use. In present study, energy metric analysis was carried out by considering the key constituting components of a solar PV plant. Similar studies were carried out for hybrid PV modules (Tiwary, Barnwal, Sandhu, and Sodha 2009 23) and to a complete standalone PV system (Sharma and Tiwary 2013 24) as found in the literature.

##### **7.4.1. Determination of system embodied energy ( $E_{emb}$ )**

For evaluating the energy performance of a PV plant, it is essential to identify the total input energy laid into such a system. This input energy includes the total energy consumed for the production of different components of PV system vis-à-vis PV

modules, supporting structure, inverter, cables etc. Estimate for embedded energy for finished product considers every stage of its lifecycle (cradle to gate) from the extraction of feed stocks to processing and assembly of individual components to finished products. Energy requirements in the packaging and delivery of finished products also need to be considered. This will follow the energy consumption in the installation/commissioning stage. Operation and maintenance phase along with the recycling phase can also be considered for complete life cycle assessment. It has to be acknowledged that complete life cycle data for all system components are not available. While there is a large variation the data involved in the transportation and delivery stage, not enough studies are conducted for end of life data for the PV system.

In our system, we aimed to in analyzing the major components of PV Modules and inverter. The data used for the study is based on a literature survey. While the embodied energy for inverter in the manufacturing phase is given in thermal energy, the thermoelectric conversion efficiency of 35% (Sharma and Tiwary 2013 24) is used to represent in equivalent electric energy. Transportation data available in the literature is not used for individual components and is included as the percentage of total embodied energy of the system along with energy consumed in operation and maintenance. **Table 7.9** indicates the calculation for embodied energy for PV modules and Inverters.

Table 7.9- System embodied energy calculation

Sl. No.	Total Embodied Energy in Manufacturing of PV panel	980	
1.	Total Energy in Commissioning	351.75	
2.	Total Embodied energy excluding inverter	1331.75	kWh/m <sup>2</sup>

3.	Total No. of Modules	1536	-
4.	Area of each Module	1.9404	m <sup>2</sup>
5.	Total module Area	2980.4544	m <sup>2</sup>
6.	Total Embodied energy excluding inverter	3969220.147	kWh
7.	Total Embodied Energy in Manufacturing and commissioning of Inverter	49700	kWh
8.	Total Embodied energy of PV panels and Inverters	4018920.147	kWh
9.	Annual Operation & maintenance and Transportation	401892.0147	kWh
10.	Total system embodied energy E <sub>embod</sub>	4420812.162	kWh

#### 7.4.2. Annual energy output

Based on the designed system's parameters and meteorological data for the location, a comprehensive simulation was carried out with PVsyst. Output results indicate the annual energy generated ( $E_g$ ) by the system is 741.8 MWh. Annual energy generation forms the basis to ascertain energy repay time, energy manufacturing factor.

#### 7.4.3. Energy payback time (EPBT)

The solar project involves the expenditure of energy at different phases of process development. In the post-installation stage, energy output can be derived from the system. Hence, EPBT is the indicative factor in terms of the total time required for recovering the invested energy in system establishment.

$$EPBT = \frac{\text{Total Embodied Energy in the System (E}_{emb})}{\text{Annual Energy Output (E}_g)} = \frac{4420812}{741800} =$$

$$5.96 \text{ years} \dots \dots \dots (10)$$

#### 7.4.4. Energy production factor (EPF)

It is described as the proportion of the system's annual energy output to its overall embodied energy. This is the performance indicator of the PV system.

$$\text{EPF} = \frac{\text{Annual Energy Output (Eg)}}{\text{Total Embodied Energy in the System (Eemb)}} = \frac{741800}{4420812} = 0.168 \dots \dots \dots (11)$$

#### 7.4.5. Life cycle conversion efficiency(LCCE)

It is described as the net energy productivity of the system relative to the total solar radiation input over course of the system lifetime of 30 years (L) considered here.

$$\text{LCCE} = \frac{\text{Life Cycle Energy Output} - \text{Total Embodied Energy}}{\text{Total incident solar radiation during Lifetime}} = \frac{(\text{Eg}) * \text{L} - (\text{Eemb})}{(\text{E})_{\text{sol}} * \text{L}} = 0.123 \dots \dots \dots (12)$$

#### 7.4.6. Capacity utilization factor

Capacity Utilization Factor (CUF) is the ratio of the annual energy generated by a photovoltaic plant to the annual equivalent energy production at that plant's rated capacity. Solar radiation and a number of clear sunny days are required for PV project energy generation.

$$\% \text{CUF} = \frac{\text{Annual energy generated per unit kWp Capacity} * 100}{8760 \text{ hrs}} = \frac{(\text{Eg}) * 100}{(\text{kWp plant}) * 8760} = 16.93\% \dots (13)$$

It is found that all the above energy metric parameters are within satisfactory limits for the designed plant. Data used for this analysis doesn't consider the recent advancement

in manufacturing processes. With the advancement in the manufacturing process in the solar sector, it is expected that embodied energy parameters tend to decrease thus making the energy metrics lucrative compared to above present values.

### 7.5. Financial assessment of plant

Investment in projects involves an upfront capital expenditure and hence it is offered to study the financial feasibility of this project prior to its execution. A well-established financial feasibility study helps in minimizing the capital risk and can also help in maximizing the returns from a specific investment. An attempt has been made to carry out a detailed financial assessment for a project. The data used in the present analysis was based on a recent market survey and current inflation rates. Key parameters and assumptions made in this financial assessment were listed in **Table 7.10**.

Table 7.10- Base parameters for financial assessment

Sl. No.	Parameter	Values					
1.	Initial capital Investment	₹24,800,000					
2.	Discount rate (proposed)	6%	8%	10%	12%	15%	20%
3.	Inflation Rate (as on March 2020)	6.57%	6.57%	6.57%			
4.	Adjusted/Effective discount rate	-0.53%	1.34%	3.22%	5.10%	7.91%	12.60%
5.	Current Tariff (as on March 2020)	₹10.50					

6.	Annual Operation & Maintenance Cost After 10 years	₹124,000
7.	Increment in Energy Rate	2%
8.	Loan Period	10 years
9.	Plant Annual Energy Generation	741800 kWh
10.	Degradation in Plant Output Annually	1%
11.	Plant Life Cycle	30 years

Before ascertaining the initial capital investment into the project, project planning chart along with the bill of materials is finalized. List of major items is mentioned in **Table 7.11** along with the cost component. The detailed analysis proposed the capital investment value of ₹24,800,000.

Table 7.11- Plant cost estimation

<b>Bill of Materials</b>		
<b>Item Description</b>	<b>Unit Cost (₹/Wp)</b>	<b>Total Cost (₹)</b>
PV modules	22	11,000,000
Inverters/Power Conditioning Units	5	2,500,000
Module Mounting Structures	4	2,000,000
Array Junction Boxes	0.8	400,000

Solar DC cables	2	1,000,000
Lightning and Earthing system	0.4	200,000
AC Power and Control cables	2	1,000,000
ACDB boxes	0.8	400,000
Metering system	2	1,000,000
Grid Interfacing unit	0.4	200,000
Energy Monitoring and BMS system	0.2	100,000
Safety equipment, operations and maintenance of the system	6	3,000,000
Installation and commissioning	4	2,000,000
	49.6	24,800,000

Operation and maintenance cost for a plant lifetime is assumed to be 0.5% of the initial investment and is examined for a period of 20 years. The cost analysis can be very detailed and we have used a simplified methodology using Microsoft Excel environment. The feasibility of the project was analyzed by considering different values of discount/opportunity rates. The initial study was conducted without adjustment for the inflation rates and later current inflation rates (MOSPI 2020 ) were considered to study the project cost.

Financial assessment of the project was made with five different discount rate options as for the loan period of 10 years. Tariff rate of ₹10.50 was considered which is currently levied from the local electricity grid. Expected energy rate from the grid is considered from ₹10.50 to ₹18.65 over the period of 30 years from now, based on the past tariff charts of the grid. An annual increment of 2% in tariff rate from the grid was assumed for the plant life of 30 years and 1% annual degradation in plant energy output is

considered for a financial assessment. Calculation methodology by considering the discount rate of 6%, wherein energy available for usage from PV plant is derived from the PV syst. “Net outflow” calculated indicates the equated yearly instalments paid against the initial investment of ₹24,800,000 which considered for the period of 10 years.

Annual maintenance cost from 11<sup>th</sup> year was considered as a component of net outflow. Calculated “Inflow savings” indicates the amount of savings made due to the utilization of the energy generated from the PV plant when compared to the same amount of energy consumption drawn from the local grid. “Net cash flow” indicates the difference in “net outflow” and “inflow savings”. “Cumulative cash flow” is found in comparison with the initial investment made with the “net cash outflow”. “Present value of cash flow” for a particular year is calculated with the inputs from discount rate and net cash flow value in the specific year. With each year’s “Present value of cash flow”, “Cumulative cash flow” with respect to present value is calculated.

**Table 7.12** indicates the merit figures of the project financial analysis for the expected discount rate of 6%. NPV of cash inflows and outflows are calculated to be ₹118,961,631.87 and ₹50,394,188.27 respectively. NPV by definition is the difference in present value between cash inflows and outflows over a specific time period in order, based on the amount of initial investment. NPV for the project investment with a discount rate of 6% is calculated to be ₹68,567,443.60. This was verified here with the last column of cumulative cash flows with present value. IRR which is an estimated indicator of profitability on investment is calculated to be 21.13% with a simple repay period of 5.4 years. ROI is found to be 31.44% with the capital recovery factor of 0.0726. With an annualized uniform cost of ₹1,797,188.10, cost per unit electricity is found to be ₹2.42.

**Table 7.13** indicates the increase in cost per unit electricity by considering the annualized uniform cost and capital recovery factor. Yearly uniform cost derived in the present case is the product of CRF and NPV of investment cost consisting of both initial project investment and running cum maintenance.

Table 7.12- Result of financial assessment

Net PV of cash Outflows	₹50,394,188.27
Net PV of cash Inflows	₹118,961,631.87
Net Present Value	₹68,567,443.60
IRR	21.13%
Simple payback Period	5.4 years
Return on investment	31.44%
Capital recovery factor	0.0726
Annualized Uniform Cost	₹1,797,188.10
Cost per unit of electricity	₹2.42

Table 7.13- Calculated effective tariff for 30 years

<b>Year</b>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<b>Per unit in ₹</b>	2.42	2.45	2.47	2.50	2.52	2.55	2.57	2.60	2.63	2.65	2.68	2.71	2.73	2.76	2.79
<b>Year</b>	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

<b>Per unit in ₹</b>	2.82	2.85	2.87	2.90	2.93	2.96	2.99	3.02	3.05	3.08	3.11	3.15	3.18	3.21	3.24
------------------------------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------

A financial feasibility analysis was done by considering the various available project discount rate options from 6% to 20% given in **Table 7.14**. It was found that with the increase in discount rate percentage, NPV of the project is decreased from ₹68,567,443.60 to ₹4,639,553.94 and indicates the negative value for 20%. Similarly, IRR is decreased from 21.13% to 14.90% by increasing the simple payback period from 5.4 years to 10.29 years. Discounted payback period got increased from 6.8 years corresponding to 6% DR to 17.4 years with 15% DR. Adjusted/effective discount rate is calculated to find out the net discount rate without taking the inflation rate into consideration.

Adjusted discount rate

$$= ((\text{Discount rate} - \text{Inflation rate}) / (1 + \text{Inflation rate}))$$

..... (14)

Financial analysis of PV plant with the adjusted discount rate, Cost/kWh electricity with a nominal discount rate and Cost/kWh electricity with the adjusted discount rate calculated in **Table 7.15**, **Table 7.16**, and **Table 7.17**, respectively.

Table 7.14- Financial analysis of PV plant with a nominal discount rate

Sl. No.	Discount Rate(%)	Net Present Values (₹)	IRR	Simple Payback Period (yrs.)	Discounted Payback Period (yrs)
1.	6	68,567,443.60	21.13%	5.4	6.7
2.	8	46,015,442.19	20.21%	5.8	8.0
3.	10	29,713,872.96	19.29%	6.3	10.0
4.	12	17,620,528.41	18.38%	6.8	11.7
5.	15	4,639,553.94	17.03%	8.0	17.4
6.	20	Negative	14.90%	10.3	Never

Table 7.15- Financial analysis of PV plant with the adjusted discount rate

Sl.No.	Discount Rate(%)	Net Present Values (₹)	IRR	Simple Payback Period (yrs)	Discounted Payback Period (yrs)
1.	-0.53%	242,630,219.48	24.0%	4.5	4.4
2.	1.34%	167,531,562.55	23.2%	4.7	4.9
3.	3.22%	116,792,594.71	22.4%	5.0	5.5
4.	5.10%	81,635,120.44	21.5%	5.2	6.2
5.	7.91%	46,874,129.83	20.3%	5.8	7.9
6.	12.60%	14,594,097.34	18.1%	7.0	12.4

Table 7.16- Cost/kWh electricity with a nominal discount rate

Sl. No.	Discount Rate(%)	Capital Recovery Factor (CRF)	Annualized Cost Of Generation (₹)	Cost per unit of Electricity
1.	6	0.073	1,797,188.10	2.42
2.	8	0.089	2,139,873.46	2.88
3.	10	0.106	2,493,410.27	3.36
4.	12	0.124	2,851,558.87	3.84
5.	15	0.152	3,387,177.21	4.57
6.	20	0.201	4,251,883.31	5.73

Table 7.17- Cost/kWh electricity with the adjusted discount rate

Sl. No.	Discount Rate(%)	Capital Recovery Factor (CRF)	Annualized Cost Of Generation (₹)	Cost per unit of Electricity
1.	-0.53%	0.031	844,859.04	1.14
2.	1.34%	0.041	1,083,152.34	1.46
3.	3.22%	0.052	1,352,618.42	1.82
4.	5.10%	0.066	1,647,682.75	2.22
5.	7.91%	0.088	2,124,218.94	2.86
6.	12.60%	0.130	2,959,507.11	3.99

## 7.6. Environmental impact analysis

### 7.6.1 Life cycle assessment (LCA)

LCA study is generally carried out as per ISO14040 and ISO14044 framework by reprise four phases i.e. goal and scoping, inventory analysis, impact assessment and interpretation. It helps to make environmentally-based decisions between other options offering the same good or service. So, in recent years, its significance has dramatically increased. For the current study, the LCA framework is shown in **Figure 7.3**.

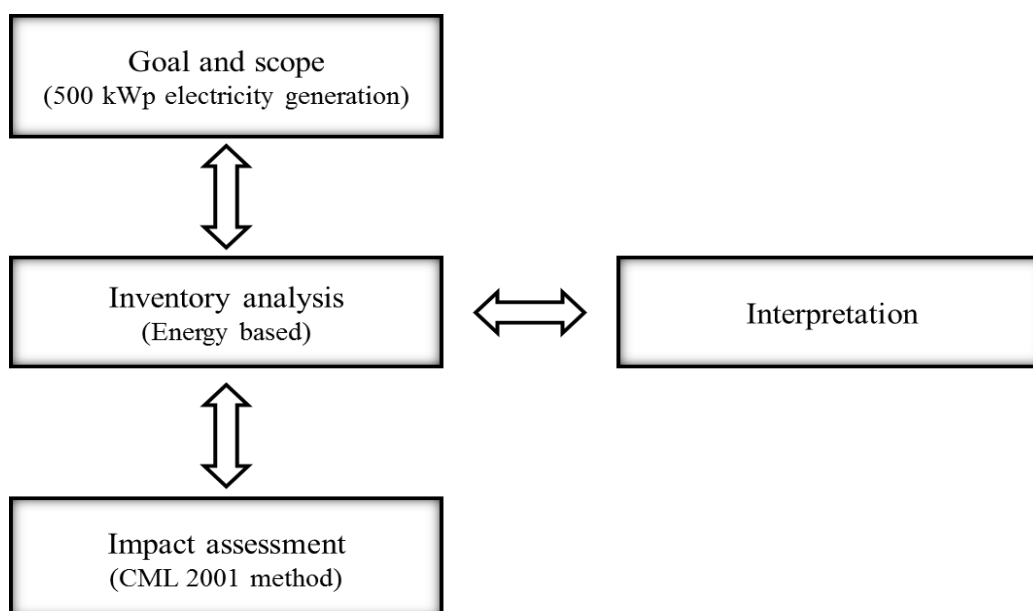


Figure 7.3- The outline of LCA study

### 7.6.2. Goal and scope

The aim of the present paper is to compare and provide a comparative generation of electricity from several sources such as coal, natural gas, nuclear, and renewable sources in India. The renewable energy sources include wind, PV, biogas, biomass and hydro. In the present study, 500 kWp electricity generation is seen as a functional component that permits a fair quantitative comparison of all.

### 7.6.3. Inventory analysis

In general, the allotment is done on three basis, the mass, the energy and the economic value, depending on its relevance. To analyze emissions during electricity generation, the energy based allocation is considered. The supplementary data is produced from the GaBi (Indian extension database). The information gathered up until the inventory phase is examined for potential environmental emissions during impact assessment. The climate crisis categories such as Abiotic Depletion Potential (ADP) for fossil fuels and elements, eutrophication potential (EP), human toxicity potential (HTP), acidification potential (AP), global warming potential (GWP), ozone depletion potential (ODP), and terrestrial ecotoxicity potential (TETP) of electricity from different sources has been accessed and contrasted. The results are provided using CML 2001 impact assessment method as its emission categories considered to be global.

Results are examined to see if they are consistent with the aim and scope during the interpretation step. According to the findings of the energy source-based environmental effect, the recommendations are organised. The utilise stage, destruction phase and reprocessing stage are not considered in the current study. The environmental impact of PV is compared with other sources for quantitative analysis.

### 7.6.4. LCA study analysis

#### 7.6.4.1. Global warming potential (GWP)

The electricity based on the coal represents the main contributor to the GWP (2.53 E+3 kg CO<sub>2</sub>-Eqiv.) followed by natural gas and biogas as shown in **Figure 7.4**. GWP of coal can differ depending on the grade of coal and boiler efficiency. It is also observed that the production of coal has lower GWP than its use phase i.e. during the combustion of coal. The GWP of coal combustion is higher due to the emission of NO<sub>x</sub> and SO<sub>2</sub>. During

the production phase of coal, mining and transportation via railways are accounted as the main contributor [153]. For natural gas, the GWP (1.42 E+3 kg CO<sub>2</sub>-Equiv.) is mainly due to extraction, liquefaction process and transportation via pipeline. The digestate's methane emissions contribute to GWP of biogas (722 kg CO<sub>2</sub>-Equiv.). The GWP from PV is only 112 kg CO<sub>2</sub>-Equiv. It helps to reduce the GWP to nearly 96% and 92% when compared with coal and natural gas respectively.

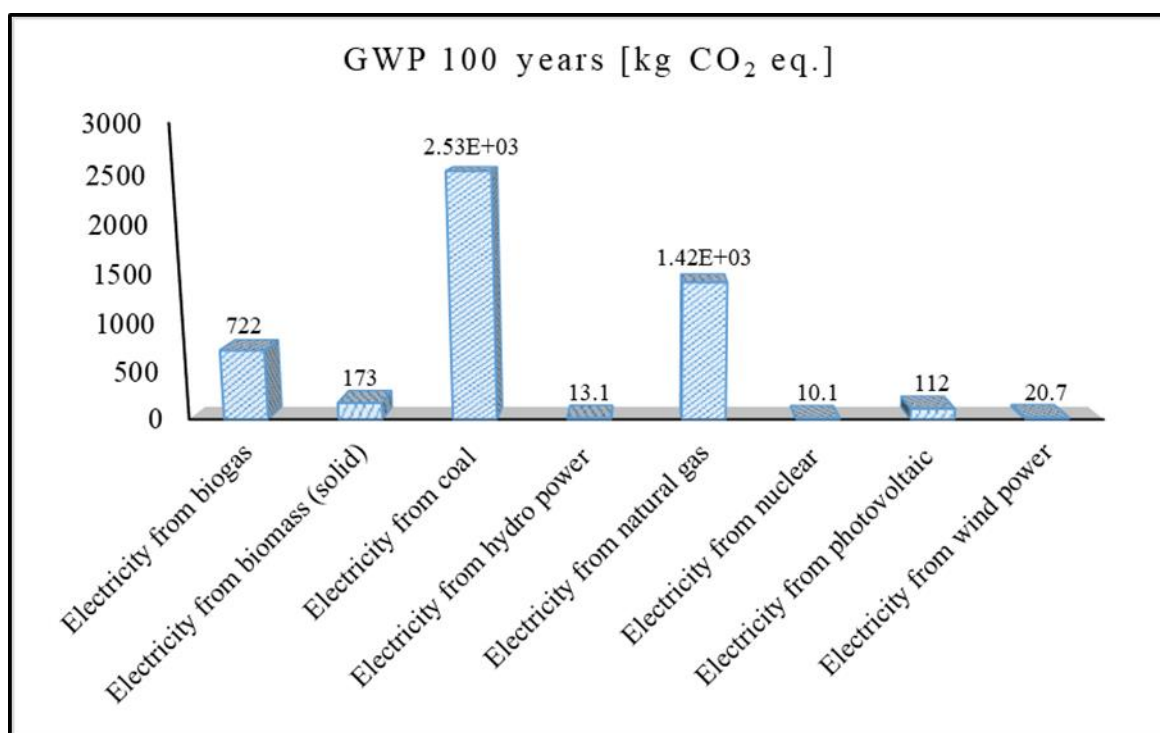


Figure 7.4- GWP of electricity generation from different sources in India

#### 7.6.4.2 Ozone depletion potential (ODP)

The ODP is highest rated for electricity generation from nuclear followed by PV. The mining and milling attributed to nuclear ODP. It is also depending on the enrichment technology used [154]. In the PV, the impact on the ozone layer is mainly due to the

manufacture of tetrafluoroethylene used in solar cell encapsulation [155]. The ODP for the PV is 95% lower than nuclear. The detailed representation for each method is shown in **Figure 7.5**.

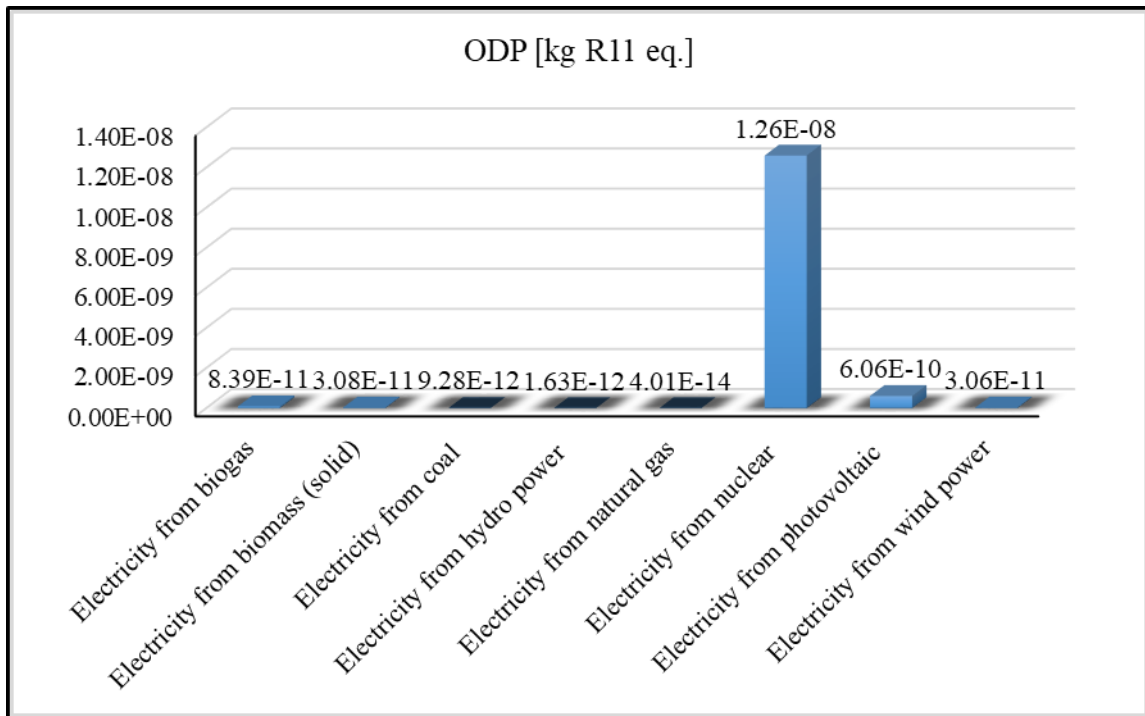


Figure 7.5- ODP of electricity generation from different sources

#### 7.6.4.3. Abiotic depletion potential (ADP) for elements and fossil

The highest ADP (elements) impact can be seen for electricity production from PV (6.60 E-3 kg Sb-Equiv.), followed by biogas (2.96 E-3 kg Sb-Equiv.), biomass (1.62 E-3 kg Sb-Equiv.) and wind energy (1.03 E-3 kg Sb-Equiv.) as shown in **Figure 7.6a**. ADP (elements) for PV is 700 times higher than coal. In PV, manufacture of the metallisation pastes primarily contribute high ADP (elements). In the case of biogas, the cultivation and associated agricultural machinery have an impact [156]. Biomass has higher emissions due to NO<sub>x</sub> emissions and land requirement compared to the hydro, nuclear

and wind [157]. For wind, the ADP (elements) is mainly due to the manufacturing of turbine components and steel.

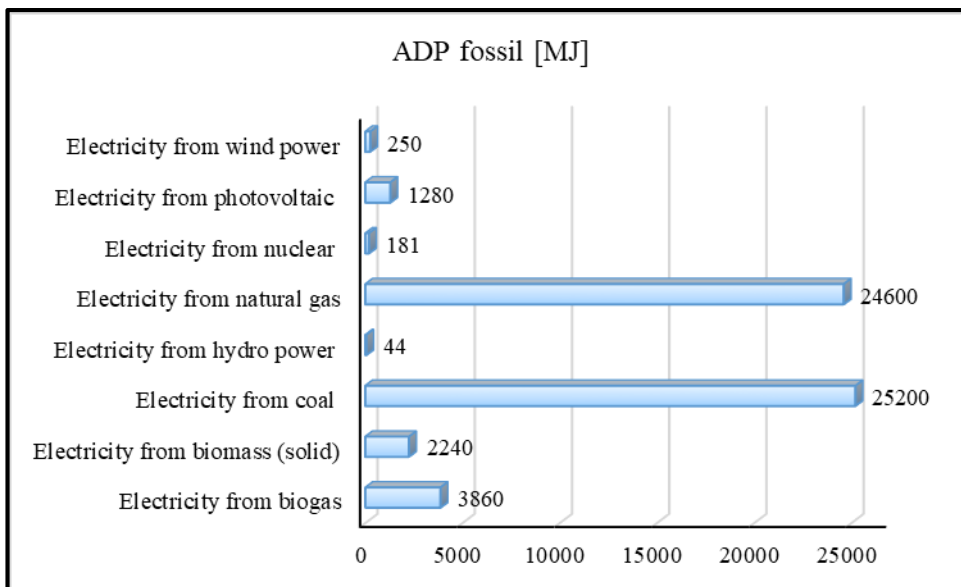
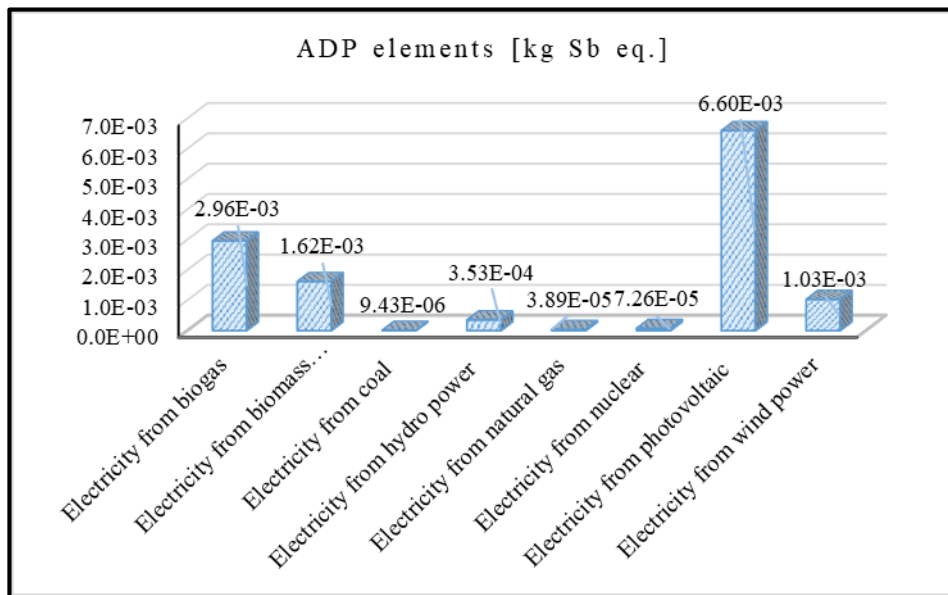


Figure 7.6- (a) and (b): ADP of electricity generation from different sources in India

ADP (fossil) is factor represents the losses caused by the mining of natural resources. Coal (25200 MJ) and natural gas (24600 MJ) account for the vast majority of the depletion of fossil resources. PV helps to save the natural resources by nearly 95% when

compared to coal for the same amount of electricity generation. The ADP (fossil) from different electricity sources is shown in **Figure 7.6b**.

#### 7.6.4.4. Acidification (AP) and eutrophication potential (EP)

The impact of electricity generation to acidification and eutrophication can be roughly estimated by NO<sub>x</sub> and SO<sub>2</sub> emissions as shown in **Figure 7.7 & Figure 7.8**, respectively. Methane and CO<sub>2</sub> emissions during mining and transportation of coal cause higher AP (21.8 kg SO<sub>2</sub>-Equiv.). The crop cultivation and ammonia released while digestate is being stored, along with acid gases and nutrients is responsible for the large majority of AP (15.6 kg SO<sub>2</sub>-Equiv.) and EP in biogas. Biomass is a considerably bigger source of NO<sub>x</sub> emissions contribute to AP (10.4 kg SO<sub>2</sub>-Equiv.) [156]. On comparison with coal, PV has around 98% lower AP and negligible contribution to EP.

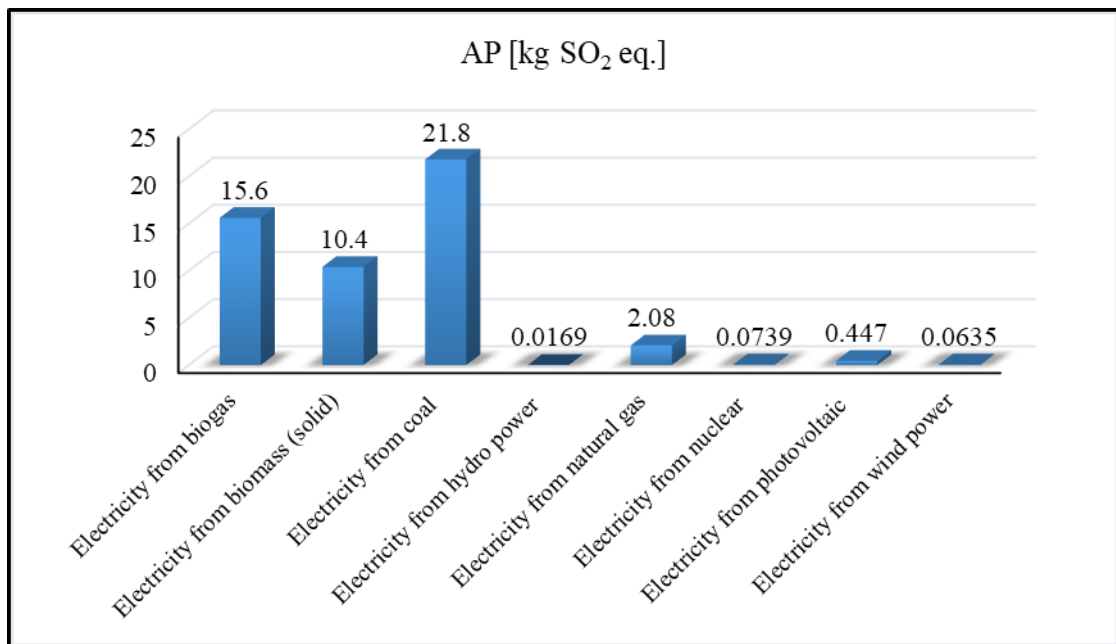


Figure 7.7- AP of electricity generation from different sources in India

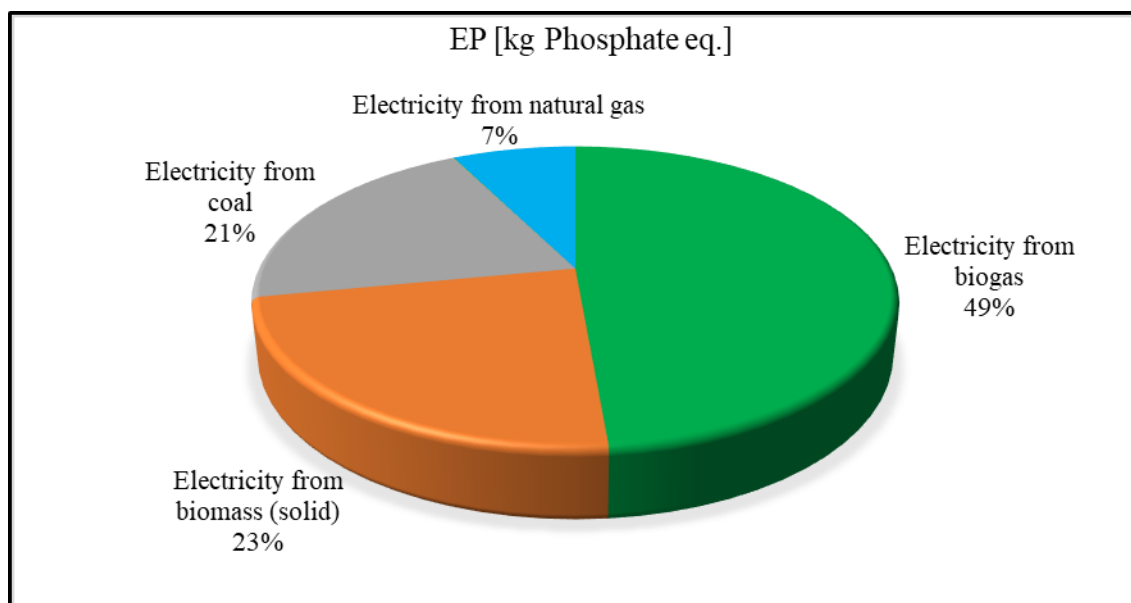


Figure 7.8- EP of electricity generation from different sources in India

#### 7.6.4.5. Human toxicity potential (HTP) and terrestrial ecotoxicity potential (TETP)

PV is the third highest contributor to HTP after coal and biomass (**Figure 7.9**). HTP is lowest for the hydro power. HTP for coal (968 kg DCB-Equiv.) is predominantly due to the chromium and arsenic [158]. Similarly, in the case of biomass, HTP (335 kg DCB-Equiv.) is mostly caused due to ash disposal. It emits heavy metals, such as chromium and vanadium, to agricultural soil [159]. The emissions from the metals production chain such as solar grade silicon manufacturing, Si-wafer etc. contribute to PV HTP (81.4 kg DCB-Equiv.)

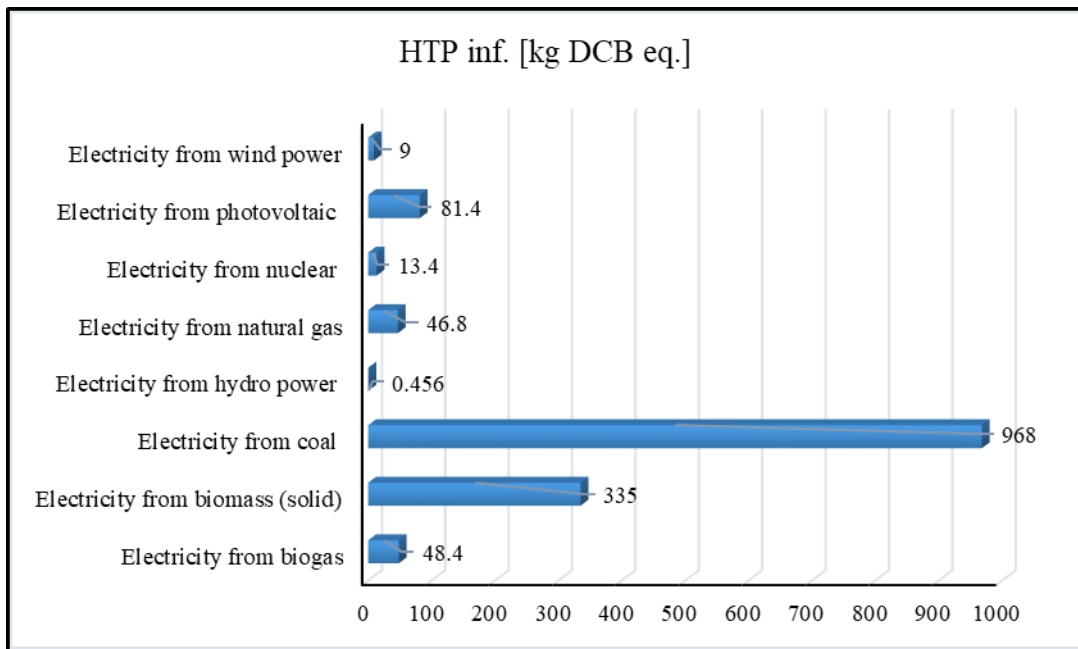


Figure 7.9- HTP of electricity generation from different sources in India

TETP is highest for biomass followed by coal. In the case of biomass, TETP is mainly due to emissions of chromium to soil. TETP is negative for biogas as its utilizing slurry and agricultural waste. PV minimizes TETP to 95% and 90% compared to biomass and coal respectively as shown in **Figure 7.10**.

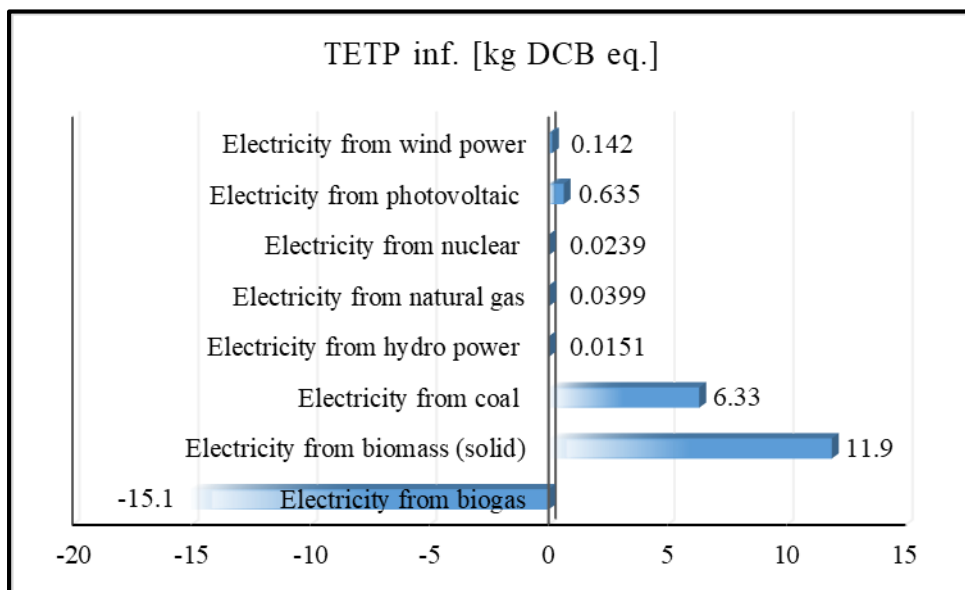


Figure 7.10- TETP of electricity generation from different sources in India

## 7.7. Summary

This study aims to provide a comprehensive assessment of a Grid Connected Roof Top Solar PV Plant. There has been an effort to prepare and analyse a techno-economic model along with its environmental impact assessment. Below is a summary of the analysis' findings-

- The 500 kWp system designed for the implementation of RTGS system in the institution requires 1550 modules each of rating 325 Wp.
- The 55.25 kWp rated east block building has 7 individual arrays each having 22 modules.
- The EPBT of the designed system is 5.96 years while the life cycle conversion efficiency is 0.123 for 30 years. The proposed plant's capacity utilisation rate is 16.93%.
- For financial assessment, an annual escalation of 2% over existing electricity tariff was considered. The inflation rates for March 2020 were considered to analyse the effect of inflation on the profitability of the project. With variation of discount rates, the project feasibility varies considerably.

The investigation reveals that the application of solar PV technology is directly influenced by financial parameters. Although there are significant benefits in terms potential savings and environmental impacts, high capital expenditure and variability in system performance are the key challenges towards its large scale implementation. The financial parameters on which present study is conducted are market driven and are hence subject to variation. For a grid connected system, it is essential to access the viability of a project for both stakeholders, i.e. the consumers and the DISCOMS. Current study

focuses on the consumer. However, project viability from the DISCOMS perspective is beyond the scope. LCA study has been used to try and analyse the environmental impacts of electricity generation from different sources such as renewable energy, coal, nuclear power, and natural gas in India. In comparison with electricity generation from natural gas, 2 out of 8 impacts are superior for electricity from coal. It has higher GWP, ADP (fossil), AP, HTP impacts than the renewable and other sources. However, solar, nuclear and biogas has higher ADP (elements), ODP and EP compared to coal respectively. Currently, renewable energy like PV and wind power is having a very small contribution in electricity generation in India. However, they will likely to achieve high growth rates in the future. Furthermore, because they fall beyond the purview of LCA, the analysis did not take into account other environmental factors including habitat loss and biodiversity loss.

With advancement in the PV technology, authors expect the capital expenditure to follow a downward trend in the near future. Authors can easily conclude that the solar PV market and technology is highly dynamic. Moreover, as more databases pertaining to Indian conditions are developed it will in turn improve the quality of data used. In future work authors will try to incorporate the effect of technological advancement and will provide a LCA and energy metric analysis which will be more accurate and specific. The economic analysis of proposed PV plant is tabulated in **Table 7.18**.

Table 7.18- Analysis of the proposed PV Plant with debt service availed at 8% per annum rate of interest.

Sl. No.	Particulars	Value
1.	Capacity of Plant	500 kWp
2.	Life of the Plant	30 years
3.	Area Required for Plant	NA
4.	Cost of Plant without Land	₹ 24,800,000
5.	Cost of Plant with Land cost	NA
6.	Savings from total energy generated in lifetime (19309.03MWh)@ Rs 10.50/kWh. (without considering any time value of money)	₹ 202,744,776
7.	Salvage value of the plant @ 15% of total Initial cost	₹ 3,720,000
8.	Simple payback period with land cost	NA
9.	Simple payback period without land cost with debt service availed at 8% per annum rate of interest	5.8 years
10.	Discounted payback with land cost & effective discount rate	NA
11.	Discounted payback without land cost & effective discount rate with debt service availed at 8% per annum rate of interest	4.9 years
12.	IRR with land cost	NA
13.	IRR without land cost	20.21%

14.	IRR with land cost & effective discount rate	NA
15.	IRR without land cost & effective discount rate	23.20%
16.	Reduce GWP compared to coal	96%
17.	Minimize ODP compared to nuclear	95%
18.	Saving ADP fossil compared to coal	95%
19.	Decrease AP and EP compared to coal	98% and 100%
20.	Minimize HTP and TETP compared to coal	92% and 90%