PERFORMANCE ANALYSIS OF GRID CONNECTED SOLAR PHOTOVOLTAIC SYSTEM

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by

Abhishek Sharma
(Roll No. 2K15/Ph.D./EE/01)

Under the Supervision of

Dr. (Prof.) Priya Mahajan
Department of Electrical Engineering
Delhi Technological University

Dr. (Prof.) Rachana Garg
Department of Electrical Engineering
Delhi Technological University

To the
Department of Electrical Engineering

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

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(Abhishek Sharma)

CANDIDATE'S DECLARATION

I Abhishek Sharma hereby certify that the work which is being presented in the thesis entitled "**Performance Analysis of Grid Connected Solar Photovoltaic System"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Electrical Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from 2015 to 2024 under the supervision of Dr. (Prof.) Priya Mahajan and Dr. (Prof.) Rachana Garg.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Candidate's Signature

CERTIFICATE BY THE SUPERVISORS

Certified that **Sh. Abhishek Sharma** (enrolment no: 2K15/Ph.D./EE/01) has carried out his research work presented in this thesis entitled **"Performance Analysis of Grid Connected Solar Photovoltaic System"** for the award of **Doctor of Philosophy** from the Department of Electrical Engineering, Delhi Technological University, Delhi, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

Signature	Signature
(Dr. (Prof.) Priya Mahajan)	(Dr. (Prof.) Rachana Garg)
(Supervisor)	(Joint Supervisor and HoD-EED)

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

Date:

Performance Analysis of Grid Connected Solar Photovoltaic System

Sh. Abhishek Sharma

ABSTRACT

The electrical power sector plays an important role in the economic growth and development of a country. In India, fossil fuels were the primary source of electricity until the last few years since then their share in the country's overall energy mix started to decline due to the limited availability and growing environmental concerns. The Government of India has committed to achieve 50% non-fossil-based installed electricity capacity by 2030. Solar energy-based decentralized and distributed generation will play a significant role in achieving this target. This commitment to solar power is backed by comprehensive policies and initiatives. The Levelized Cost of Energy (LCOE) is a key cost metric for comparing various power generation technologies, encompassing all fixed and variable costs. It represents the price at which electricity must be sold for the system to break even over its lifetime thereby helping to assess the investment viability of a project. During the early years, the solar industry faced a dual challenge: lowering the LCOE to attract consumers and distribution companies, while also protecting investor interests. The Indian government has rightly targeted this concern by directly subsidizing the solar sector through Viability Gap Funding (VGF), Generation-Based Incentive (GBI), Accelerated Depreciation (AD) etc. to bring it at par with conventional generation tariffs. This has led to a decrease in the LCOE of the solar PV projects for the consumer and thus paved the way for its faster adoption at the same time safeguarding the interests of investors. With the introduction of auction-based bidding, the industry has moved to dynamic market pricing. The withdrawal of selective support measures highlights the maturation of the solar industry.

However, the solar power photovoltaic generation is intermittent in nature and the reliance of photovoltaic power generation on various meteorological parameters impacts solar generation due to weather-induced variability. During the day, fluctuations in radiation introduce intermittency in power generated, raising reliability and grid stability issues at higher penetration levels. Storage allows intermittent sources to address timely load demand and adds flexibility in load management. It permits some of the consumptive load of one moment to be satisfied by the primary generation of another period. With the exponential growth of solar generation, it has become necessary to comprehend the working of battery energy storage systems in tandem with a grid-connected PV-based system from grid stability point of view.

Further, the performance and efficiency of the photovoltaic module are highly affected by various environmental and local weather factors. Out of many factors that determine optimum yield in a PV module, environmental factors like accumulation of dirt, dust etc. (soiling loss) directly affect the performance of solar generation. Soiling losses enhance uncertainty in solar generation and result in a rise in LCOE due to loss of energy production, and increased Operation & Maintenance

(O&M) costs. Relating weather conditions with dust accumulation on PV modules will enable us to develop better predictive models for the power output of PVs in the sense that these models will include the power losses caused by dust accumulation.

With the rapid growth of solar installations in India and the world over, managing the waste from solar PV panels has become an impending challenge. Solar panels have an estimated useful lifespan of 20-25 years before they are considered waste. Apart from this, global evidence has demonstrated that faulty or damaged panels during the early part of their lifecycle also contribute substantially to solar waste problems. The absence of adequate regulations, guidelines and operational infrastructure for photovoltaic waste in India may lead to waste being inappropriately landfilled or incinerated in a manner that may be detrimental to human health and the environment.

The thesis discusses various factors that affect the techno-economics of solar PV power generation and various components that decide the solar tariff. The extent of some of the direct incentives (VGF, GBI, etc.) and indirect incentives (waiver of transmission losses and Point of Connection (PoC) charges, exclusion from merit order dispatch/ must-run status, government policy support etc.) required to achieve a desired value of LCOE for solar PV plants have been investigated on the basis of the cost-effectiveness index. An in-depth analysis of the solar photovoltaic system's techno-economics performance will shed light on the plant's real functioning & profitability and make suitable recommendations for future projects.

The present study apart from a discussion on popular grading methods for performance evaluation of plants namely Capacity Utilization Factor (CUF) and Performance Ratio (PR), also considered the feasibility of a battery storage system from a peak demand reduction point of view using General Algebraic Modelling System (GAMS) under a variable electricity energy pricing dynamic. The energy management approach described in this study aims to reduce annual energy costs for buildings by optimizing battery energy usage.

The operational issue of soiling has been dealt with through an outdoor investigation conducted in real time in Delhi, a city having the dubious distinction of the polluted megacity of the world. In addition to estimating soiling loss using an outdoor experiment, the current study also attempts to quantify the effects of deposited and ambient particulate matter, including dust, on the solar flux that can be used to generate energy. The present study aims to address the issue of soiling by developing an optimal cleaning schedule. Such an investigation would facilitate feasibility studies of cleaning mechanisms and the development of appropriate cleaning schedules for solar panels considering pollution levels in Delhi to minimize loss of energy.

The thesis highlights the study undertaken to estimate the volume of solar PV waste in India, particularly at the time when the country is undergoing a massive solar capacity expansion programme. Presently, India is in the stage of installation of solar photovoltaic panels and little or no focus is being given towards the impending problem of handling solar waste. The study aims to estimate the volume of solar PV waste in India and also presents an environmentally benign strategy to policymakers for the handling of solar waste using LCA methodology. The role of the avoided burden approach due to recycling of materials from the point of view of circular economy prospects has been discussed.

The thesis research work is designed to delve deep into the challenges plaguing the solar industry and propose effective solutions for these challenges.

List of Publications

Journal Publication

1. A. Sharma, P. Mahajan and R. Garg, "Analysing the impact of various incentives on solar tariff in India," International Journal of Sustainable Energy, vol. 41, no. 2, pp. 126-47, 2022. DOI: 10.1080/14786451.2021.1900184. Indexing: SCOPUS, Publication: Taylor & Francis.

2. A. Sharma, P. Mahajan and R. Garg, "Sensitivity Analysis of Levelised cost of Electricity in India from SPV Plant," Water and Energy International, vol. 64, no. 7, pp. 47-54, 2021. Indexing: SCOPUS, Publication: Central Board of Irrigation and Power.

3. A. Sharma, P. Mahajan and R. Garg, "Performance and cost benefit analysis of solar photovoltaic power plant for Delhi secretariat building," Water and Energy International, vol. 60, no. 9, pp. 16-25, 2017. Publication: Central Board of Irrigation and Power.

4. A. Sharma, P. Mahajan and R. Garg, "End-of-life solar photovoltaic panel waste management in India: forecasting and environmental impact assessment," International Journal of Environmental Science and Technology, vol. 21, no. 2, pp. 1961-80, 2024. (DOI:10.1007/s13762-023-04953-2. Indexing: Science Citation Index Expanded (SCIE), Publication: Springer.

International Conference Publications

1. A. Sharma, P. Mahajan and R. Garg, "Techno-economic analysis of solar photovoltaic power plant for Delhi secretariat building.," in In2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, 2016.

2. A. Sharma, P. Mahajan and R. Garg, "Dust and cleaning impact on the performance of photovoltaic output: an outdoor experimental study," in 3rd International conference on Renewable Power-Springer, Delhi, 2024.

Book Chapter

1. A. Sharma, P. Mahajan and R. Garg, "Peak Shaving Through Battery Storage for Photovoltaic Integrated Building Considering the Time-of-Day Pricing," in Lecture Notes in Electrical Engineering, Springer, 2024, pp. 813-825.

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List of Symbols, Abbreviations and Nomenclature

ABT	Availability-Based Tariff
AD	Accelerated Depreciation
AQI	Air Quality Index
APPC	Average Power Purchase Cost
AT_{PV}	Applicable Tax
AWC_{PV}	Annual Working Capital
BAU	Business as Usual
BESS	Battery Energy Storage System
CAAQMS	Continuous Ambient Air Quality Monitoring Stations
CAPEX	Capital Expenditure
CC_{PV}	Capital Cost
CERC	Central Electricity Regulatory Commission
CFA	Central Financial Assistance
CG_{PV}	Contingency Cost
COP	Conference of the Parties
CPCB	Central Pollution Control Board
C_{PV}	Life Cycle Cost
CPSU	Central Public Sector Undertaking
CUE_{PV}	Cost Per Unit of Energy
CUF	Capacity Utilisation Factor
CT	Current Transformers
CW_{PV}	Civil and General Work Cost
DER	Demand Side Management
DERC	Delhi Electricity Regulatory Commission
DoP	Department of Power
DR_{PV}	Discount Rate
DSM	Demand Side Management
DF_{PV}	Discount Factor
DTU	Delhi Technological University
EoL	End-of-Life
EPR	Extended Producer Responsibility
E_{PV}	Lifetime Energy Production
EVA	Ethylene Vinyl Acetate
FRELP	Full Recovery End-of-Life Photovoltaic
FU	Functional Unit
FIT	Feed-In Tariff
FOR	Forum of Regulators
GAMS	General Algebraic Modelling System
GBI	Generation-Based Incentive
GHG	Greenhouse Gas
GHI	Global Horizontal irradiance
GoI	Government of India
GNCTD	Government of National Capital Territory of Delhi
GWP	Global-warming potential
ICC	Interest on Construction

IDC	Interest During Construction
IEA	International Energy Agency
IMD	India Meteorological Department
IOL_{PV}	Interest on Loan
IPCC	Intergovernmental Panel on Climate Change
I_{sc}	Short Circuit Current
ISO	International Organization for Standardization
ISTS	Inter State Transmission Systems
IRR	Internal Rate of Return
IWC_{PV}	Interest on Working Capital
JNNSM	Jawaharlal Nehru National Solar Mission
LC_{PV}	Land Cost
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LCIA	Life Cycle Impact Assessment
LiFE	Lifestyle for Environment
MC_{PV}	Module Cost
MDI	Maximum Demand Indicator
MG	Metallurgical-Grade
MOD	Merit Order Dispatch
MoEFCC	Ministry of Environment, Forest and Climate Change
MOM_{PV}	Monthly Operation and Maintenance Expenses
MNRE	Ministry of New and Renewable Energy
MS_{PV}	Maintenance Spares
MSS_{PV}	Mounting and Supporting Structure Cost
NAMP	National Air Quality Monitoring Programme
NCR	National Capital Region
NDCs	Nationally Determined Contributions
NPL	National Physical Laboratory
NPV	Net Present Value
NSM	National Solar Mission
NTPC	National Thermal Power Corporation
O&M	Operation and Maintenance
PCU_{PV}	Power Conditioning Unit Cost
PLI	Performance Linked Incentives
Pmax	Maximum Power
PM	Particulate Matter
PM-KUSUM	Prime Minister Kisan Urja Suraksha Evam Utthaan Mahaabhiyan
PoC	Point of Connection
PPC	Power Purchase Cost
PPA	Power Purchase Agreement
PR	Performance Ratio
PT	Potential Transformers
PV	Photovoltaics
RE	Renewable Energy
REC_{PV}	Receivable Energy Charge
RES	Renewable Energy Sources

RoE	Return on Equity
$RORE_{PV}$	Rate of Return on Equity
R&M	Repair and Maintenance
SCADA	Supervisory Control and Data Acquisition
SECI	Solar Energy Corporation of India Limited
SEM	Scanning Electron Microscope
SERC	State Electricity Regulatory Commission
SL	Soiling Loss
SNAs	State Nodal Agencies
SoC	State of Charge
SPM	Suspended Particulate Matter
ToD	Time of Day
T & D	Transmission and distribution
t/MW	Tonnes/Mega Watt
VGF	Viability Gap Funding
Voc	Open-Circuit Voltage
WACC	Weighted Average Cost of Capital
WEEE	Waste Electric and Electronic Equipment
XLPE	Cross-linked Polyethylene
Y_F	Final Yield
Y_R	Reference Yield
XRF	X-ray fluorescence

CHAPTER 1

INTRODUCTION

1.1 Introduction

For any country, there exists a strong relationship between electricity consumption and economic growth. The means adopted for electrical energy generation should be secure, sustainable, economical, environment friendly and socially acceptable. The rising consumption of fossil fuels (and associated prices), together with increased greenhouse gas emissions, threatens secure energy supply for a developing country like India. The lack of sufficient energy supply can also hold back the growth of the nation therefore the need is for the development of clean, secure, sustainable and affordable energy sources. The obvious choice of a clean energy source for a nation like India is Sun's energy which is abundantly available and could provide energy security. Within the Indian context, solar photovoltaic generation is favoured over other renewable energy alternatives due to the abundance and intensity of solar radiation [1]. Most parts of India receive daily solar radiation ranging from 4–7 kWh/m^2 with sunny days, varying between 250 to 300 days annually [2]. India as per commitment in Conference of Parties 26 (COP), Glasgow, U.K has set an ambitious plan for achieving 50% of India's total installed capacity for electricity from non-fossil sources including solar generation by 2030. This commitment may not only augment power generation but also contribute largely to green energy production to help reduce climatic changes.

With the installation of 175GW of generation capacity through renewable in the last nine years, the Indian power sector has experienced a significant transition from a power deficit to a power surplus nation [3]. India made a commitment at the COP-21, Paris (France) to attain 40% of its installed electrical capacity from non-fossil energy sources by 2030 as part of its Nationally Determined Contributions (NDCs). The country has achieved this target in November 2021 i.e., 9 years ahead of schedule. India is currently heading toward meeting the updated targets from Glasgow's COP26, which states that by 2030, non-fossil fuel sources will account for 50% of installed capacity for power generation.

The Indian grid has now emerged as the world's largest integrated grid that can transmit power up to 1,12,250 MW through Inter-State Transmission Systems (ISTS). During, February 2023 in rural areas, the average power availability per day has increased from 12 hours in 2015 to 22½ hours while the average availability in cities is 23½ hours. Around 24% of power is generated by the central sector, 25% is generated by the state sector and the rest 51% is generated by the private sector. The nation's overall generation, which includes power from renewable sources connected to the grid, increased from 1110.458 BU in 2014–15 to 1624.465 BU in 2022–2023 [4]. The details of installed generation capacity (Fuel-wise) as of 30.06.2024 is given in Table 1.1 [5].

Table 1.1 Installed Generation Capacity Details (Fuel-Wise)

	Installed Generation Capacity (MW)	Percentage share in total
Fossil (Coal/Lignite/Gas /Diesel)	**242996.91**	**54.46%**
Non-Fossil		
Hydro	46928.17	10.51%
Wind	46656.37	10.45 %
Solar	85474.31	19.15 %
Bio Mass Power/Cogen	10,355.35	2.32 %
Waste to Energy	593.36	0.13 %
Small Hydro Power	5005.25	1.12 %
Nuclear	8180.00	1.83%
Total Non-Fossil Fuel	**203192.81**	**45.54%**
Total Installed Capacity (Fossil Fuel & Non-Fossil Fuel)	**4,46,189.72**	**100%**

India stands 5th in solar PV deployment across the globe at the end of 2022 [6] [7]. The share of various sources of energy based on installed capacity is shown in Fig. 1.1

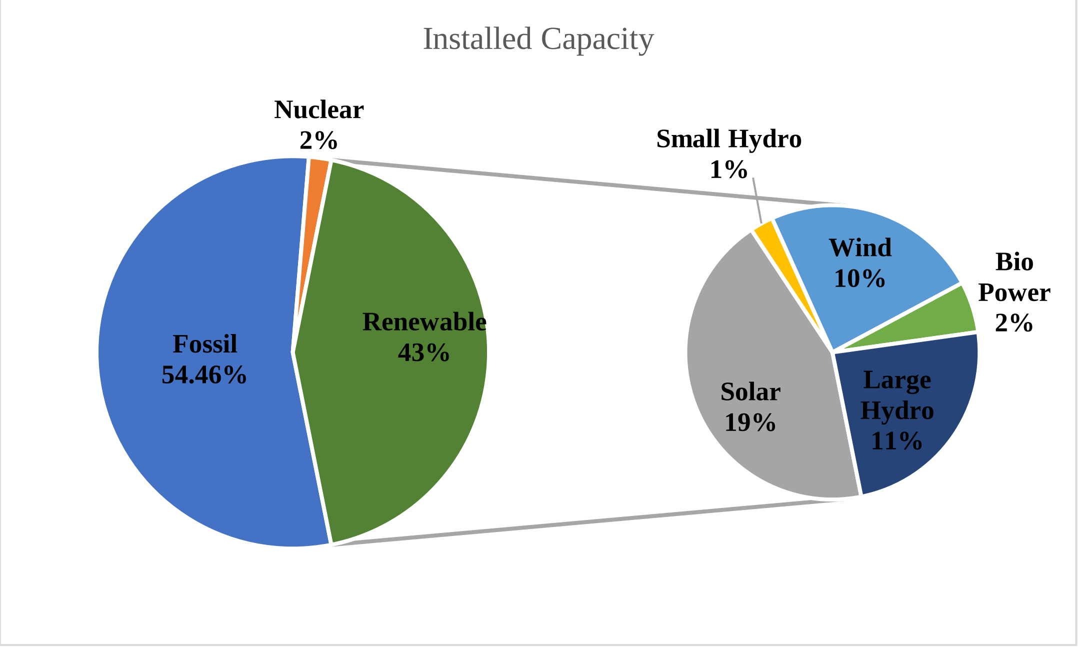

Fig. 1.1 Share of various sources of energy based on installed capacity [8]

1.2 Current Status of Solar Energy Generation in India

There has been a visible impact of solar energy in the Indian energy scenario during the last few years. Millions of people in Indian villages have benefited from solar energy-based decentralized and distributed applications by meeting their energy needs for cooking, lighting, and others in an environment-friendly manner. The social and economic benefits include a substantial decrease in the drudgery experienced by girls and rural women due to the collection and transport of fuel wood over long distances and cooking in smoke-filled kitchens and, a reduction in the risk of developing lung and eye conditions, the creation of jobs at the village level, and, finally, an improvement in overall living standards. Furthermore, over time, India's solar energy sector has grown to become a significant contributor to the country's grid-connected power production. It supports the government's agenda of sustainable power generation. The two principal classifications of solar PV systems are grid-connected or utility-interactive systems and stand-alone systems or off-grid connected systems. Various policies and initiatives support these classifications.

1.2.1 Grid-Connected System

Grid-connected solar photovoltaic systems use power conditioning units or inverters to convert the DC electricity produced by solar panels into AC power, which is then fed into the power grid. This category includes the creation of solar parks and ultra-mega solar power projects, the rooftop solar programme, the Central Public Sector Undertaking (CPSU) Scheme Phase-II (government producer scheme), and Prime Minister Kisan Urja Suraksha Evam Utthaan Mahaabhiyan (PM-KUSUM). As of June, 2024, the country had installed 82.03 GW of grid-connected solar power [8].

1.2.2 Off Grid System

Off-grid solar systems, which operate independently, are a feasible way to boost energy availability in rural areas where the conventional grid is not entirely dependable. To meet the electricity and lighting needs of the local communities, institutions, and individuals in rural areas, the nodal ministry, the Ministry of New and Renewable Energy (MNRE), has been offering Central Financial Assistance (CFA) for the deployment of solar street lights, solar study lamps, and solar power packs under the off-Grid and decentralized solar PV applications program. State Nodal Agencies (SNAs) are primarily responsible for implementing the program. Additionally, the PM-KUSUM Scheme is being used to develop standalone solar pumps, solarize already-existing agricultural pumps, and install grid-connected solar power plants up to 2 MW under this category. As of June 2024, the country has installed 3.44 GW of off-grid solar out of 85.47 GW of installed solar power [8].

1.2.3 Solar Energy Policy/Targets in India

The Indian Government's commitment towards solar energy is backed by comprehensive policies and initiatives. The brief of some of the major solar policies, targets and commitments made by various state and central governments at various national and international forums that are shaping solar energy growth in the country are given in Table 1.2.

Table 1.2 Brief Details of Major Solar Policies, Targets and Commitment

S. No.	Name of Scheme/Policy	Brief Details
1.	**Jawaharlal Nehru National Solar Mission (JNNSM)**	The JNNSM was initially launched in January 2010 under the brand name 'Solar India'. The JNNSM is a major initiative of the Government of India and state governments to promote ecologically sustainable growth while addressing India's energy security challenge. The JNNSM aimed to achieve 20,000 MW of grid-connected solar projects by 2022 and later in June 2015, the targets were enhanced by five times to attain 1,00,000 MW by 2022.
2.	**Government of India Commitments in COP**	India during the 26th session of the Conference of the Parties (COP26) at Glasgow (U. K.) in August 2022 updated its NDC by presenting to the world five nectar elements (Panchamrit) of India's climate action including the target of net-zero emissions by 2070 as follows: • To attain 50% of India's total installed capacity for electricity from non-fossil sources by 2030. • To reduce the GDP's emission intensity by 45% from levels in 2005 by 2030. • To promote and further disseminate a moderation- and conservation-based lifestyle that is healthy and sustainable, for example, by organizing a large-scale LiFE (Lifestyle for Environment) movement.
3.	**Solar Tariff Policies**	Solar power tariffs are determined either through the regulations of the Central Electricity Regulatory Commission (CERC) /State Electricity Regulatory Commission (SERC) or through competitive bidding. The levelized tariff is calculated by carrying out levellisation for the 'useful life' of PV technology considering the discount factor for the time value of money. The tariff period is for 25 years and the ratio of debt to equity is 70:30. Due to the continuous fall of Levelized Cost of Energy (LCOE), the government has discontinued the practice of declaration of benchmark cost and now tariffs are decided through competitive bidding.

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S. No.	Name of Scheme/Policy	Brief Details
4.	**Performance Linked Incentive (PLI) Scheme**	To reduce reliance on imports in the field of solar energy this scheme was launched to encourage the production of highly efficient solar PV modules. With an investment of Rs. 24,000 crores, an effort is being made to achieve Giga-Watt (GW) levels of domestic manufacturing capacity for solar PV cells and modules. There are two phases to the implementation of the scheme tranche I and II, which have an outlay of Rs. 4,500 crore and Rs. 19,500 crores respectively for identified bidders [9].
5.	**Green Open Access Rules**	The Green Open Access Rules, 2022 aimed at promoting renewable energy and eliminating obstacles related to the availability and utilization of RE. The rules lower the 1 MW open access limit to 100 kW thus allowing small users to purchase RE without any restrictions and for captive consumers, there is no capacity limit. Customers have the right to request discoms to supply them with green power. Discoms are obligated to procure and provide green power to eligible consumers

1.3 Challenges Affecting Solar PV Growth

The complete solar cycle right from manufacturing to the end of the life cycle stage can be broadly divided into four steps as shown in Fig.1.2.

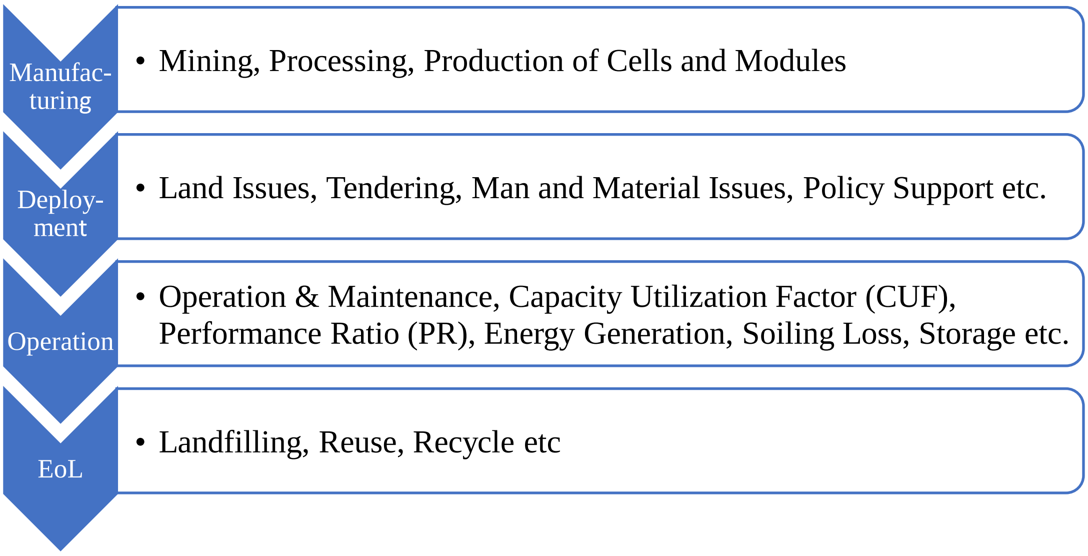

Fig.1.2 Broad Categorisation of Complete Solar Cycle

Despite various conducive policies and targets set by the government for the overall growth of the solar industry, the industry is still facing certain challenges like the land issues, challenges in the regulatory framework, reluctance on the part of state discom's, soiling issues, solar e-waste problem, lack of research and development, solar energy integration issues with grid, storage challenges, issues pertaining to long term Power Purchase Agreements (PPA), financing models and arrangements etc. that hinders the growth of solar sector.

1.4 Motivation for Research

The Levelized Cost of Energy (LCOE) is widely used to compare different types of power generation technologies by considering the various fixed and variable costs as a single cost metric. It is the price at which the generated electricity should be sold for the system to break even at the end of its lifetime. LCOE is used to determine whether or not a project is a worthwhile investment [10]. Solar tariff determination is a complex phenomenon and has not been elaborated in a way to understand its nuances in any of the studies conducted so far. Moreover, studies done so far are focused on the need for incentives for the growth of the Indian solar energy sector but none have pointed out the effect of comparison of various incentive schemes on solar LCOE. Such type of comparisons is required for decision-making by the policymakers, solar power developers, and other stakeholders involved to rationalize the incentives provided.

The majority of renewable energy sources including solar are unable to deliver energy continuously and may cause an imbalance between supply and demand, particularly during off-peak hours when renewable energy produces more energy than during peak hours. Inefficient grids result from too much solar output in the afternoon and too little during the night, which increases the requirement for electricity production during the night or during cloud cover. Storage allows intermittent sources to address timely load demand and adds flexibility in load management. It permits some of the consumptive load of one moment to be satisfied by the primary generation of another period. Various studies have already been conducted to analyse the performance of solar PV plants based on data of annual/monthly generation to cater to building load profile characteristics but only a few have examined the role of battery energy storage systems in coordination with a grid-connected PV-based system to maximizes the annual benefits to the building.

The energy output delivered from a solar PV module depends greatly on the amount of irradiance that reaches the solar cells. Out of many factors that determine optimum yield in a photovoltaic module, environmental factors like accumulation of dirt, dust etc. (soiling loss) directly affect the performance of solar generation. Soiling losses enhance uncertainty and result in the rise of LCOE due to loss of energy production, increased O&M costs, and higher finance rates. It has been observed that the soiling phenomenon although seems to be simple to calculate mathematically, in practical is a complex problem affected by climatic conditions, localized pollution, mounting configuration etc. The studies conducted so far are concentrated on energy loss and merits/demerits of various cleaning mechanisms attributable to soiling based on outdoor and indoor experiments conducted at different locations the world over. Given the enormous investments being made in solar PV power plants throughout India, it is important to comprehend the long-term performance of PV modules in the

Indian climatic conditions, since the energy yield will determine the return on investment. Relating weather conditions with dust accumulation on PV modules will enable us to come up with better predictive models for the power output of PVs in the sense that these models will include the power losses caused by dust accumulation.

With the rapid growth of solar installations in India, managing the waste from solar PV panels has become an impending challenge. PV panels not only include harmful substances like lead that cause significant health and environmental risks, when incorrectly disposed. The waste streams also contain rare and valuable materials that are lost due to lack of insufficient facilities for recycling and recovery. The solar waste problem will turn into a serious environmental problem in the next decades unless addressed at this stage.

1.5 Research Objectives

The present thesis has undertaken the challenges by incorporating them as research objectives:

i. Solar tariff determination: Impact of various incentives on solar levelized cost of energy.
ii. Performance evaluation of a grid-connected PV plant integrated with a battery energy storage system.
iii. Assessment of dust soiling impacts and determination of cleaning frequency for performance improvement.
iv. End-of-life solar photovoltaic panel waste management in India.

1.5.1 Solar Tariff Determination: Impact of Various Incentives on Solar Levelized Cost of Energy

The structured approach of tariff determination, ensures fairness, and encourages the growth of solar energy. There is a need to understand the various components that decide the solar tariff and the various factors that affect the techno-economics of solar PV power generation. The extent of some of the potential incentives (viability gap funding, generation-based incentive, etc.) needs to be investigated to achieve the desired value of LCOE. An in-depth analysis of the solar photovoltaic system's techno-economics performance will shed light on the plant's real functioning & profitability and make recommendations for improvement in future projects.

1.5.2 Performance Evaluation of a Grid-Connected PV Plant Integrated with Battery Energy Storage System

Apart from discussion on popular grading methods for Performance evaluation of plants namely Capacity Utilization Factor (CUF) and Performance Ratio (PR), there is a need to understand the feasibility of a battery storage system from a peak demand reduction point of view under a variable electricity energy pricing dynamic. This energy management approach will not only reduce annual energy costs by maximizing battery energy throughput with grid restrictions acting as network demand limits but also provide input for government authorities, policymakers, and other stakeholders like investors, project developers, etc. to develop regulations and policies for the promotion of battery storage in installations wherein distributed sources of energy and BESS are being used in coordination.

1.5.3 Assessment of Dust Soiling Impacts and Determination of Cleaning Frequency for Performance Improvement

The solar panel's efficiency is greatly influenced by deposition of dust particles on the surface of the panels. There is a need to establish experimentally the influence of dust on the performance and output of solar PV systems. Such an investigation would facilitate feasibility studies of cleaning mechanisms and the development of appropriate cleaning schedules for solar panels to minimize loss of energy.

1.5.4 End-of-Life Solar Photovoltaic Panel Waste Management in India

Solar power from an energy requirement point of view promises a bright future for India, but behind the gleam is a growing mountain of e-waste. Presently, India is in the stage of installation of solar photovoltaic panels and presently no focus is being given towards the impending problem of handling solar waste. With the current growth rate of solar PV, the solar waste problem will turn into a serious environmental problem in the next decades unless addressed at this stage. There is a need for a comparative study to present an environmentally benign strategy to policymakers for the handling of solar waste based on LCA analysis.

1.6 Organisation of Thesis

The current chapter provides an introduction to the thesis and gives an overview of the Indian power sector, various solar energy policies/targets in India, motivation for research along with research objectives and challenges affecting solar PV growth in India.

Literature review pertaining to solar tariff determination: impact of various incentives on solar levelized cost of energy, performance evaluation of a grid-connected PV plant integrated with battery energy storage system, assessment of dust soiling impacts and determination of cleaning frequency for performance improvement and end of life solar photovoltaic panel waste management in India has been carried in **Chapter 2**. Chapter 2 also presents identified research gaps and measures to eliminate the identified research gaps.

Chapter 3 focuses on the determination of the levelized cost of energy and factors affecting LCOE, a comparison of various factors is done on the basis of the cost-effectiveness index.

Chapter 4 presents analysis of grid-connected solar PV plant on basis of the CUF and PR along with peak shaving through battery energy storage solution using

General Algebraic Modelling System (GAMS) software.

Chapter 5 focuses on the results of the experimental set-up conducted to study the effect of environmental factors on soiling loss in Delhi and the development of an optimal cleaning schedule.

Chapter 6 presents solar waste assessment in India using the Weibull function along with an environmental impact assessment of PV waste using LCA analysis through SimaPro software.

A detailed conclusion along with the scope of future work and, the social impacts of the present study followed by references is presented in **Chapter 7**.

1.7 Concluding Remarks

This chapter provides an overview of the present status of solar generation particularly in India and associated challenges. The motivation for research and research objectives is also outlined. The research work undertaken in each chapter is summarized.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The challenges and goals of the current research work are described in Chapter 1. A brief literature review has been carried out on the following topics:

i. Solar tariff determination: Impact of various incentives on solar levelized cost of energy
ii. Performance evaluation of a grid-connected PV plant integrated with battery energy storage system
iii. Assessment of dust soiling impacts and determination of cleaning frequency for performance improvement
iv. End-of-life solar photovoltaic panel waste management in India

Each topic is briefly reviewed in the following sections without trying to be exhaustive. The references in this chapter are also representative rather than exhaustive.

2.2 Solar Tariff Determination: Impact of Various Incentives on Solar Levelized Cost of Energy [11-26] & [94-117]

To make solar energy a mainstream source of power generation, the Indian government has taken several initiatives in the last decade. Presently, the deployment of solar power projects in India is governed by both central and state governments under various schemes [11]. The importance of government support can be judged by the fact that China has taken the lead as compared to other countries in the solar industry mainly due to the technological production of solar panels and governmental support [12].

Shrimali and Rohra [13] reviewed the national solar mission and provided an analysis of the Jawaharlal Nehru National Solar Mission (JNNSM) in the Indian institutional context—in particular, in the context of the power sector reforms. Branker and Pathak [14] have studied methodology for the evaluation of the levelized cost of energy to determine the economic feasibility of PV projects. The paper reviews the methodology for precisely calculating the LCOE for solar PV, thereby correcting various misconceptions. Then, a template is provided for better reporting of LCOE results for PV that are needed to influence policy mandates or make investment decisions.

The weighted average prices of various power production systems can be objectively compared using the levelized cost of energy/electricity [10].The LCOE values are not comparable to the amount of feed-in compensation or the price of energy, which includes other expenses like taxes, subsidies, and other incentives that may affect the final cost of power. For individual power facilities, LCOE is a suitable tool for making initial investment decisions [15].

Several studies [16] [17] [18] [19] [20] have pointed out many barriers acting as hindrances to achieving the target set by NSM however, the central/state governments and regulatory bodies have taken many path-breaking initiatives like Accelerated depreciation (AD), Viability gap funding (VGF), Generation Based Incentives (GBI), etc. to address the impediments to the NSM. These policy instruments have led to rapid growth in the Indian renewable energy sector, at over 20% during the period 2010–17.

Papadelis et.al. [21] presented an approach to facilitate ongoing assessments of the efficiency of support measures for renewable energy sources (RES-E) deployment and also demonstrated the proposed approach using the feed-in tariff (FIT) support policy in Greece as a case study.

The paper [22] studied the profitability reduction in various PV investments due to the modified legislative and regulatory framework in Greece over the years from 2009 to 2014. To quantify the impacts, a full parametric analysis was conducted. The analysis shows that the impact on the profitability of PV stations is largely mediated by parameters such as the size of the station and the PV activation date (affecting installation costs and respective profit margins) as well as the option of subsidy taking.

The majority of research on India was descriptive or qualitative in nature, focusing on either deployment barriers [23] or factors conducive to investors [21]. A number of case studies have analysed the renewable energy regulatory framework and implementation across two states [24] and also across multiple states [25]. Since solar deployment in India is now largely driven by states, the study [26] strives to comprehend the various state-level drivers for enhanced solar deployment in the country.

2.3 Performance Evaluation of a Grid-Connected PV Plant Integrated with a Battery Energy Storage System [27-52] & [118-125]

Due to growing environmental concerns and exponentially rising energy demands world over, the integration of decentralized energy sources like solar and wind into current conventional power systems has acquired greater significance. Decentralized sources at the user end decrease the demand for increased generation and transmission capacity as well as benefits like bill savings and reduced transmission congestion. However, solar PV and wind are variable sources, and there are several challenges associated to the temporal variability of its electricity output [27] [28] [29] [30] [31]. Several energy storage technologies, including batteries [32] [33]. superconducting magnetic energy storage [34], flywheels [35], super-capacitors [36], and fuel cell/electrolyser hybrid systems [37], can be used to address this issue. In the study [38], it has been demonstrated that with the installation of a battery system of a capacity of 92 kWh in the sports building of Tampere University of Applied Sciences, Finland, the electric power taken from the grid was limited to 65 kW and in addition, latent heat thermal energy storage technique developed by Munich University of Applied Sciences was simulated for peak shaving of district heating. As per simulation results, thermal energy storage leads to shaving off of peaks of district heating power, subject to that the power limit is taken according to the total heat demand. BESS helps in capacity firming, peak load shaving, power arbitrage, frequency regulation, and improving power quality [39] [40] [41]. Storage systems lead to a reduction in the peak power and losses, but will also increase the investment cost however, the nation by significantly boosting production capacity and battery manufacturing competence can contribute economically to this crucial sector [42].

The results of a utility-run rooftop photovoltaic power plant equipped with battery energy storage systems are presented in the study [43] as a workable option for improving grid resiliency and energy storage at the distribution network level. Integration of energy storage plants with demand apart from providing balancing services to the grid also enables deferral of distribution infrastructure upgradation [44]. The investigation on the aggregated benefits of storage due to the placement of storage in the distribution network has been carried in the studies [45] [46] [47].

In the paper [48] optimization problem of renewable energy resources and the BESS in planning islanded micro-grids is solved using the general algebraic modelling system. The effect of an increase in the Time of Use (ToU) as well as block rate tariff in Anhui province, China, has been studied for assessing the opportunity for building integrated photovoltaic systems [49]. The effect of market-based energy pricing on the performance of the operation of the distributed network in coordination with renewable energy systems was studied in detail [50] [51] [52].

2.4 Assessment of Dust Soiling Impacts and Determination of Cleaning Frequency for Performance Improvement [53-78] & [126-162]

Dust naturally blocks sunlight from reaching the photovoltaic cells, which can drastically reduce the module's power output, and thus accounting for soiling loss. Numerous studies on the effects of soiling on solar system performance have been carried out in various countries. Mani and Pillai [53] examined the research conducted from 1940 to 2010 and provided an overview of the influencing factors, including dust properties, wind velocity, ambient temperature and humidity, PV system tilt angle, glazing, and site characteristics. They also provide general mitigation measures recommendations for various climatic zones. The relationship between macroscopic environmental factors and the micro-scale characteristics of dust particles, such as particle adhesion and removal forces, on the overall dust accumulation was investigated in the study [54]. During duration of two weeks, the power output of the photovoltaic modules dropped by about 6.5% compared to normal power output. The density of dust in Athens was 1 g/m^2 [55]. The photovoltaic power generation in Indonesia reduced by 10.8%, in two weeks of dust accumulation [56]. There was a constant power loss of 3% to 4% after 5 weeks in Belgium due to dust accumulation [57]. Around 5 g/m^2 dust density was observed on the solar modules in Saudi Arabia after they were tilted at a 26° angle for 45 days, and the transmittance decreased by 20% [58]. The types of soiling are reviewed in detail [59], and the literature also provides a detailed compilation of the benefits and drawbacks of various soiling mitigation strategies. It has been pointed out that choosing the best technique is challenging and depends on several variables, including site circumstances, resource availability, PV system capacity, expectations, and economics. Various cleaning strategies have been proposed in the literature [60] to mitigate the detrimental effects of soiling in 2019 and presented a thorough analysis of the influence of all environmental elements on PV performance and their strategies for mitigation, including cleaning frequency and mechanisms. The impact of dust on solar modules is examined in [61], wherein the effect of the dust on the real-time data gathered from 46 inverters with a total monthly production of 114819.30 kWh, or 4416.13 kWh per day, has been analysed.

According to Lu and Zhao [62], dust deposition has less of an impact on rooftop installations than ground installations; dust deposition is higher on fixed tilt angle PV installations than on PV installations with sun tracking systems. The effect of dust on the performance of PV systems in semi-arid and desert areas of southern Algeria having higher solar density evaluated by Bouraiou et. al. [63]. Frequent PV cleaning is required to prevent deterioration of the performance of the PV system. In the study [64] it has been demonstrated that due to the deposition of dust, the loss in cost of electrical energy outweighs the cost of regular cleaning. The study by Astitva et.al [65] involves an assessment of the reduction in PV power generation due to dirt derating factor (K_d) for a 6300 Wp solar PV system in Saudi Arabia. The impact of dirt, dust, and soiling on the system is studied and a robust empirical model has been developed. The study by Kumar et.al [65] involves an assessment of the reduction in PV power generation due to dirt derating factor (K_d) for a 6300 Wp solar PV system in Saudi Arabia. The impact of dirt, dust, and soiling on the system is studied and a robust empirical model has been developed.

Manju et al. [66] investigated a variety of PV cleaning techniques, including wet cleaning and dry cleaning with the use of a cloth, a mechanical brush, compressed air, ultrasound, vibration, and many other tools. According to Chaichan et al. [67], the kind, nature, and surrounding landscape of the dust should all be taken into consideration while choosing the right cleaning technique. In the study [68] it has been revealed that rainfall is more effective in eliminating bigger dust particles than smaller ones (2–10 µm). McTainsh et al. [69] state that the size of the dust deposition on the surface of the photovoltaic panels corresponds to the distance from which the wind carries the dust; these solid particles are smaller than 500 μm. The diameter of deposited dust can range from less than 5 μm when it is brought in from long distances, between 20 and 40 μm when it is deposited from regional sources, and between 50 and

70 μm when it is deposited due to local vehicle movement and the anthropogenic impact [70] [71] [72] [73].The role of hydrophobic or hydrophilic materials for coating to prevent dust accumulation on the solar panel is discussed in detail [74] [75] [76] [77]. A study at King Abdulaziz University (KAU), Jeddah, Saudi Arabia found a power increase of 27 % for a water-based cleaning mechanism however air jets and module vibration were found less successful in removing soiling [78].

2.5 End-of-Life Solar Photovoltaic Panel Waste Management in India [79-93] & [163-210]

World over, the major thrust is on the improvement of production efficiency, and very little or no attention is paid to the slowly but surely increasing the photovoltaic (PV) waste problem. Various studies conducted in different regions across the world have estimated different values of accumulation of solar waste. Domínguez and Geyer [79] estimated that in Mexico for each GW of installed PV capacity, around 4 million PV modules waste will be generated by 2045, and PV modules will constitute 691 thousand metric tonnes of PV waste. In another study done for the USA by the same authors [80], it is estimated between 2030 and 2060, a total of 9.8 million metric tons of PV waste will be generated that including 6.6 million metric tons of PV modules waste, 2.7 million metric tons Balance of System (BOS) waste, 0.3 million metric tons inverters waste, and 0.215 million metric tons transformers waste. Paiano [81] projected the PV crystalline silicon waste amount in Italy for two periods i.e., between 2012–2038 and 2039–2050 based on the 25-years lifetime of PV panels. The estimated amount during 2012–2038 is 1,957,099 tonnes, corresponding to the photovoltaic installations from 1987 to 2013, and the amount during the period 2039–2050 is 6,281,868 tonnes, corresponding to the installations during 2014–2025. Peeters et. al. [82] highlighted the uncertainty in estimating the PV waste volumes owing to the rapid development of PV technology. The authors estimated the amount and material composition of waste from silicon-based PV modules based on the theory of the bathtub curve in Flanders, Belgium. Faircloth et.al. [83] estimated that in Thailand, 5000 t of PV waste will have accumulated by 2025 and by 2030, the country will be producing at least 8000 t of PV waste per year. Similarly, actual PV installation in Australia from 2001 to 2018 formed the basis for the fact that 0.8 million tonnes of cumulative PV waste will be generated by the year 2047 based on the study by [84] [85] using SimaPro 8.0.4.30 and ReCiPe midpoint impact assessment method to compare two treatment scenarios that include high and low recovery rates in a laboratory scale and highlighted that the recycling of the PV panels generates large environmental benefits at the material recovery level as well as the scale of the biosphere (pollution prevention).

The study [86] estimates the volume and composition of end-of-life solar PV waste for the European Union and the United States along with the potential of recycling of generated waste as per the regulations. Federal and municipal rules must be supportive in order to build a strong reverse supply chain logistics system for PV panels. As of the middle of 2023, there was no federal law in the US controlling the specifics of EoL management for solar PV panels. [87] [88].

The level of recycling streams is important as recovered products from high-value recycling streams, such as from aluminium recycling, are of high quality like virgin materials and they provide substantial economic benefits [89]. Conversely, low-value recycling streams struggle to pay for the costs of the recycling process and produce low-revenue products [90].

A pilot scale project named Full Recovery End-of-Life Photovoltaic (FRELP) for the treatment of the EoL crystalline PV modules was studied by Latunussa et. al. [91] for conducting the environmental impact assessment of the EoL PV panels based on the industry data. This study excludes the analysis of the production of secondary raw materials. For India, a study by Pankadan et. al. [92] predicted 0.4 million tonnes and 0.038 million tonnes of waste due to early and regular losses. respectively by 2030, and 7.99 million tonnes and 3.61 million tonnes, due to early and regular losses respectively by 2050. Presently, solar PV module and battery waste are considered general electronic waste and its effective and safe disposal comes under the Ministry of Environment, Forest and Climate Change (MoEFCC), even despite the presence of e-waste regulations in place since 2011, only 5% of the estimated e-waste is recycled in the organized or formal sector [93].

2.6 Identified Research Gaps

Despite the fact that numerous studies have been carried out in the field of identified research objectives, many challenges still remain unsolved. Based on the extensive literature research indicated above in the previous section, the following research gaps were identified.

2.6.1 Solar Tariff Determination: Impact of Various Incentives on Solar Levelized Cost of Energy

Most of studies conducted till now has concentrated on the need for incentives to support the expansion of the solar energy industry in India but none has elaborated the process of solar tariff determination and demonstrated in detail the effect of various incentive schemes on solar LCOE. The literature surveyed failed to provide a comparison of various incentive schemes for decision-making by the policymakers, solar power developers, and other stakeholders involved.

2.6.2 Performance Evaluation of a Grid-Connected PV Plant Integrated with a Battery Energy Storage System

Various studies have already been conducted to analyse the performance of solar PV plants based on data of annual/monthly generation to cater to load profile characteristics. However, only a few studies have examined the role of battery energy storage systems in coordination with a grid-connected PV-based system along with the determination of the optimal size of the BESS that maximizes the annual benefits to the building.

2.6.3 Assessment of Dust Soiling Impacts and Determination of Cleaning Frequency for Performance Improvement

The studies conducted so far are concentrated on energy loss and merits /demerits of various cleaning mechanisms attributable to soiling based on outdoor and indoor experiments conducted at different locations the world over. There is a need to determine the optimal frequency of solar panel cleaning to minimise loss of solar generation.

2.6.4 End-of-Life Solar Photovoltaic Panel Waste Management in India

From the literature survey, it has been observed that most of the studies are concentrated particularly on solar PV waste estimation, life cycle, and economic assessment of PV panels, but still, there are considerable gaps in these studies, as the success of the EoL solution of solar PV panels depends on the robustness of local regulatory and policy framework and overall participation of various stakeholders viz. original equipment manufacturers, solar PV system installers, consumers, recyclers, and various government organizations. None of these studies conducted so far has highlighted the enormity of the impending solar PV waste problem in India. There is a need to present an environmentally benign strategy to policymakers for the handling of solar waste.

The present thesis has undertaken various systematic measures to eliminate the identified research gap.

2.7 Concluding Remarks

This chapter provides a review of the literature on identified research objectives. The contribution of various prior research, reports, scholarly articles etc. has been outlined. The studies already conducted provided a solid starting point for accomplishing the task undertaken in the present thesis. The chapter also highlights the research gaps along with measures to eliminate them.

CHAPTER 3

SOLAR TARIFF DETERMINATION: IMPACT OF VARIOUS INCENTIVES ON SOLAR LEVELIZED COST OF ENERGY

3.1 Introduction

Globally, in 2022, the new capacity addition in the solar PV market achieved the largest ever recorded increase of 243 GW increasing the total capacity of solar PV installation to approximately 1185 GW. Fig.3.1 illustrates the progress of solar PV capacity globally from 2009-2022 [94].

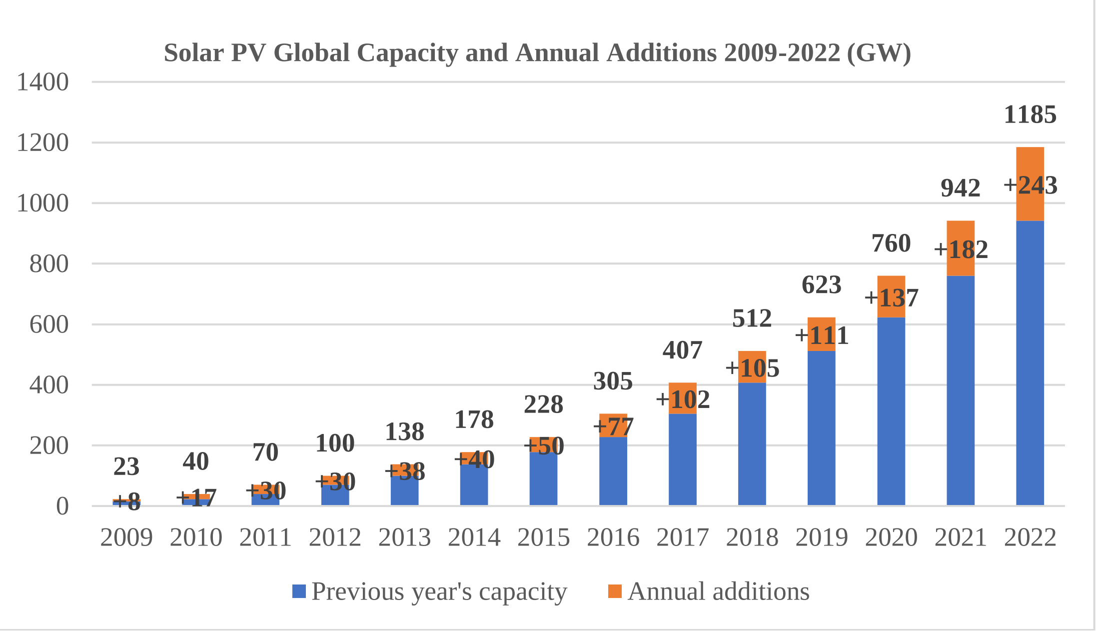

Fig. 3.1 Progress of Solar PV Capacity Globally from 2009-2022

The economics of solar power have undergone a considerable shift in recent years, making it a more attractive option than ever before. Solar PV has demonstrated the highest learning rates among all renewable power generating technologies that is, the percentage reduction in cost for every doubling of the cumulative installed capacity of a technology. Utility-scale solar PV has the highest estimated learning rate during the period 2010 to 2022, at 33.1%. The reported learning rate for the same duration for concentrating solar-thermal power and onshore wind was 18.1% and 20.6% respectively [95].

Solar energy holds great potential for providing a solution to the long-standing energy issues continuously faced by developing countries like India [96] [97] [98] [99]. India's solar tariffs have witnessed a steep decline in recent years since the announcement of revised targets for the National Solar Mission (NSM) in the year 2015, making solar power increasingly competitive with traditional fossil fuels.

The major factors that have contributed to the decline of the solar tariff are a reduction in the cost of solar cells and other associated components, the adoption of more efficient production techniques, government impetus through various incentives, and enhanced competition and scale of projects. To regulate renewable energy tariffs, the levelized tariff of various technologies of generation including solar is determined by the Central Electricity Regulatory Commission with and without Accelerated Depreciation (AD). AD allows greater deductions in the earlier years of the life of an asset than the traditional straight-line method. In the year 2010-11, when NSM was first announced, the levelized tariff for solar as issued by CERC stood at Rs. 17.91/kWh without AD and Rs. 14.95/kWh with AD for 25 years and it decreased by 68 per cent to Rs. 5.68/kWh without AD and by 66 per cent to Rs. 5.08/kWh with AD in 2016-17 [100] [101]. Since 2017, with the introduction of competitive tariff-based bidding, the tariff has been coming down continuously. This breakthrough cost-cutting was made possible mainly by central and state government impetus through various incentive schemes.

In this study, an attempt has been made to discuss various direct and indirect incentives available for the promotion of solar PV installation in India. The effect of various incentives on solar LCOE is also compared based on the cost-effectiveness index. Although the study is done keeping in mind the solar tariff scenario in India however, the policymakers of other countries can benefit from the outcome of this study during the formulation of policies and incentive schemes for their respective countries.

3.2 Components of Solar Tariff

In India, the tariff of electricity from solar PV plants is calculated in accordance with CERC regulation "Terms and Conditions for Tariff determination from renewable energy sources regulations" [100] [102] [103] [101]. Tariff for any generation plant generally has two components a) capacity component and b) energy component. The capacity component is also called the fixed cost component and it is that component of tariff that must be given to the generator (irrespective of energy scheduled to the plant) for recovery of investment made with a fair rate of return and day-to-day running expenses. The energy component is also called the variable cost component and it depends on fuel cost used to generate actual output. However, the tariff of electricity from solar PV plants is a single-part tariff with only a fixed cost component. In the case of the SPV plant, the tariff period is for twenty-five years and its basic cost components are:

i. Interest on Loan (IOL_{PV}) capital
ii. Return on Equity
iii. Depreciation
iv. Interest on Working Capital
v. Operation and Maintenance Expenses

3.2.1 Interest on Loan Capital

The share of equity is 30%, and the remaining amount of capital cost for installation of a solar power project i.e., 70% is raised using debt. Typically, debt loans have a term of 10 to 12 years. The loan duration may be extended beyond 15 years as the risk perception is improving for the solar energy industry. The interest rate on solar power projects varies from 10.5%-13%.

3.2.2 Return on Equity

For the calculation of tariff, the debt-equity ratio considered is 70:30. The 30% parts is raised through equity from investors. It is the Return on Equity (RoE) by which a sector becomes attractive or unattractive for investors on which all investors keep an eye. CERC provided a high rate of return on equity of 20% per annum for the first 10 years and 24% per annum from the 11th year onwards for solar PV which is one of the highest in the sector. A high rate of RoE not only means more profitability for the investor but also brings more investment in the sector.

3.2.3 Depreciation

Depreciation is the reduction in value of assets due to wear and tear every year. Depreciation acts as a cash flow instrument for tax-shield and permits projects to write off their losses thereby helping solar energy projects to save taxes. Three different methods are followed for depreciating the solar asset.

i. **CERC defined depreciation rates:** For a 12-year loan period, CERC regulates asset depreciation at 5.83% and 1.54% for a period beyond that

ii. **Book depreciation method:** The cost of an asset is annually recorded in the book of accounts using this method. Its rate remains constant at 5.28% throughout the duration of the project.

iii. **Accelerated depreciation method:** A larger deduction from taxable income is possible using the accelerated depreciation technique. Up to 40% of costs can be reduced in the first year and, projects could recover up to 80% of the benefits of AD. Enhanced deduction from taxable income strengthens cash flow and returns.

3.2.4 Interest on Working Capital

Liquidity for solar energy projects is guaranteed through working capital or short-term loans. In India, loans with terms ranging from a few months to a year are considered short-term loans. Due to their short lifetime, they often come with a high interest rate ranging between 12% and 14%.

3.2.5 Operation and Maintenance Expenses

Operation and Maintenance (O&M) of solar plants is done to ensure that all parts and components of a solar plant work in an efficient manner and provide optimum energy generation. O&M comes into the picture after the installation and commissioning of plants. O&M of solar energy projects are of three types:

i. **Preventive Maintenance:** It foresees a problem likely to occur in advance and takes necessary steps to resolve these problems. e.g., due to the gathering of dust, the output of solar panels gets reduced therefore periodic cleaning is required to maintain generation levels.

ii. **Breakdown Maintenance:** It comes into the picture when a plant or a component fails suddenly such as inverter failure or external factors damaging solar panels during normal plant operation.

iii. **Real-Time Monitoring:** Digital recorders are used to capture real-time data regarding solar energy generation, solar radiation and other parameters. Any deviation from reference production requires an urgent call to action.

Table 3.1 Values of Various Solar PV Project Parameters.

Parameter	**Details**	**Values**
Financial Assumptions	Tariff period Capital cost/MW Debt: Equity Debt Equity	25 years Rs. 530.02 lakh Rs. 371.02 lakh (@70 %) Rs. 159.01 lakh (@ 30%)
O&M Expenses	O&M expenses (2016-17) O&M expenses escalation	Rs. 7.00 lakh @5.72% per annum
Depreciation	Depreciation rate for first 12 years Depreciation rate 13th year onwards	@5.83% @ 1.54%
Interest on Term Loan (IOL_{PV})	Loan repayment period is 12 years	@ 12.76%
Interest on Working Capital (IWC_{PV})	**For fixed charges** O&M charges Maintenance spares (as % of O&M expenses) Receivables for debtors For variable charges	 1 month 15 % 2 months 13.26%
Return on Equity (ROE_{PV})	(ROE_{PV}) for the first 10 years (ROE_{PV}) 11th Year onwards	@20.00% p.a. @24.00% p.a.

The values of each component as per the CERC tariff order 2016-17 are given in Table 3.1 [101]. Operation and maintenance (O&M) expenses comprise repair and maintenance expenses, establishment expenses (including employee expenses), and administrative and general expenses. These expenses are taken as Rs. 7.00 Lakh with an escalation of 5.72% per annum. The depreciation of asset shall be allowed up to a maximum permissible value of 90% of the capital cost and salvage value shall be considered as 10%. Depreciation shall be chargeable from the first year of commercial operation and for part of the year, it shall be charged on a pro-rata basis. The rates have been considered as 5.83% for the first 12 years and 1.54% from the 12th year onwards. The rate of interest on the loan is determined from the average base rate prevalent during the first six months of the previous year plus 300 basis points e.g., during the first six months of FY 2015-16, the base rate was 9.76% resulted in interest rate @ 12.76% for FY 2016-17. The renewable energy tariff regulations provide a method for the determination of annual working capital requirements of the PV projects as under (a) One-month O&M expenses; (b) Two months receivables energy charges; (c) Maintenance spares @ 15% of O&M expenses.

The Return on Equity (RoE) is taken as 20% per annum for the first 10 years, and 24% per annum from the 11th year onwards. Based on the parameters given in Table 3.1 [101], the solar tariff for the year 2016-17 as issued by CERC can be calculated as given in Appendix-II (Table II.1) In recent years, the solar tariffs have fallen to new levels and thus, have re-invigorated the power sector of India. Table 3.2 shows the trends of cost components and effective levelized tariffs as issued by CERC from FY 2010 to FY 2017 [100] [102] [103] [101]. The levelized tariff is calculated by carrying out levellisation for the 'useful life' of PV technology considering the discount factor for the time value of money. Discount factor denotes the factor by which a future cash flow must be multiplied to obtain present values.

Table 3.2 Summary of CERC Generic Tariff Orders for Solar PV Technologies from FY 2010 – FY 2017.

Period	**FY 2010-11**	**FY 2012-13**	**FY 2015-16**	**FY 2016-17**
Capital Cost (Rs. lakh/ MW)	1690	1000	605.85	530.02
Discount Rate	15.97%	10.62%	10.81%	10.64%
Depreciation Rate for First 12 Years	7.00%	5.83%	5.83%	5.83%
Depreciation Rate 13th Year Onwards	1.33 %	1.54%	1.54%	1.54%
Interest on Working Capital	12.89%	12.80%	13.50%	13.26%
O&M Expenses (Rs. lakh/ Annum)	9.51	11	13	7
Levelized Tariff (Rs. /unit)	17.91	10.39	7.04	5.68
AD Levelized Benefit (Rs. /unit)	2.96	1.04	0.69	0.60
Effective Tariff (Rs. /unit)	**14.95**	**9.35**	**6.35**	**5.08**

It can be seen that capital cost has reduced from Rs. 1690 lakh/MW in the year 2010-11 to Rs.530.02 lakh/MW in the year 2016-17, a reduction of around 69%. It is mainly because of a decrease in the cost of PV modules in international markets over the years, which form a major portion of the capital cost.

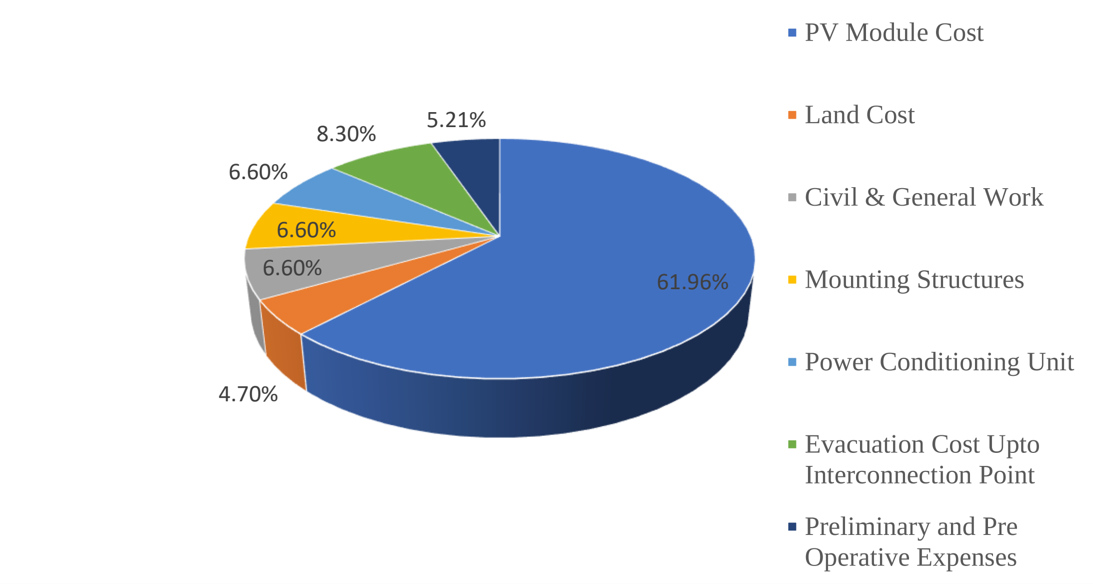

Fig. 3.2 Bifurcation of Components of the Capital Cost of Solar PV-Based Power Projects.

In the year 2016-17, the PV module component share was around 62% of capital cost as can be seen in Fig. 3.2 [104]. Sensitivity analysis is a modelling tool used to analyse how different values of an independent variable affect a particular dependent variable under a certain set of pre-defined assumptions. LCOE is sensitive to variations in the values of module cost, VGF, GBI, and discount rates. The CERC till 2017 annually reviewed benchmark cost norms based on comments of various stakeholders involved to determine the levelized cost of energy.

3.3 Determination of Levelized Cost of Energy

The Levelized cost of energy is the price at which the generated electricity should be sold for the system to break even at the end of its lifetime. It is calculated by carrying out levellisation for 'useful life' considering the discount factor for the time value of money. LCOE aims to provide a comparison of various technologies with respect to different project sizes, lifetimes, different capital costs, returns, risks, and capacities. For levelized tariff computation, the discount factor equivalent to post-tax Weighted Average Cost of Capital (WACC) is considered. LCOE can be calculated using Eqn. 3.1 [14] [105] [106].

$$\text{LCOE} = \text{Life cycle cost } (C_{PV}) \,/\, \text{Lifetime energy production } (E_{PV}) \quad (3.1)$$

Components of fixed costs are return on equity, interest on the loan, depreciation, interest on working capital and operation and maintenance expenses so the life cycle cost of the complete project shall be the Net Present Value (NPV) of these Fixed Cost (FC)/cash flows as given in Eqn. 3.2 to 3.3.

$$C_{PV} = NPV\ (FC_{PV1} + FC_{PV2} + \ldots\ldots\ldots + FC_{PV25}) \tag{3.2}$$

$$C_{PV} = \sum_{i=1}^{25} \{FC_{PVi} / (1+d)^{i}\} \tag{3.3}$$

where d is the discount rate

Similarly, lifetime energy production shall be the net present value of energy generated by the plant annually (kWh) as given in Eqn. 3.4 to 3.5.

$$E_{PV} = NPV\ (kWh_{PV1} + kWh_{PV2} + \ldots\ldots\ldots\ldots + kWh_{PV25}) \tag{3.4}$$

$$E_{PV} = \sum_{i=1}^{25} \{kWh_{PVi} / (1+d)^{i}\} \tag{3.5}$$

Therefore, LCOE can be written as given in Eqn. 3.6 – 3.8.

$$LCOE = \sum_{i=1}^{25} \{FC_{PVi} / (1+d)^{i}\} / \sum_{i=1}^{25} \{kWh_{PVi} / (1+d)^{i}\} \tag{3.6}$$

Whereas $1 / (1+d)^{I}$ is the Discount factor i.e., DF_{PVi}

$$LCOE = \sum_{i=1}^{25} \{(FC_{PVi} \text{ x } DF_{PVi}) / kWh_{PVi}\} / \sum_{i=1}^{25} \{DF_{PVi}\} \tag{3.7}$$

$$LCOE = \sum_{i=1}^{25} \{CUE_{PVi} \text{ x } DF_{PVi})\} / \sum_{i=1}^{25} \{DF_{PVi}\} \tag{3.8}$$

where CUE_{PV} is the cost per unit of energy and DF_{PV} is the discount factor in a financial year.

There are several methods to evaluate the economic viability of distributed generation projects. The capital cost of assets, the operation and maintenance costs, and the fuel costs must be considered in a systematic way so that a comparison can be made. The LCOE is dependent on the following factors and has been estimated using a spreadsheet (Microsoft Excel) based program using Eqn. 3.9 to 3.12:

i. **Capital Cost:** The various components of capital cost and their weightage are shown in Fig. 3.2 [104]. It can be seen that capital cost (CC_{PV}) can be broadly divided into module cost and non-module cost components. PV module cost (MC_{PV}) forms a significant component of the overall capital cost of the PV-based power plant and varies from 60-65% of overall capital cost and is highly dependent on PV module prices in the international market. The non-module cost component that typically varies from 30%-40% of the overall capital cost comprises Power Conditioning Unit Cost (PCU_{PV}), Land Cost (LC_{PV}), Mounting and Supporting Structure Cost (MS_{PV}), Civil and General Work Cost (CW_{PV}), Transportation/Evacuation cost (TC_{PV}), and preliminary and pre-operative expenses including Interest During Construction (IDC) and Contingency Cost (CG_{PV}). The expression presenting capital cost is given by Eqn. 3.9.

$$CC_{PV} = MC_{PV} + LC_{PV} + CW_{PV} + MS_{PV} + PCU_{PV} + TC_{PV} + CG_{PV} \quad (3.9)$$

ii. **Discount Rate (DR_{PV}):** The present value is determined by using an assumed interest rate, usually referred to as a discount rate is the rate at which an investment's revenues and costs are discounted to calculate its present value and it is used to calculate the discount factor. In India, in compliance with renewable energy tariff regulation, the discount factor is considered equal to the post-tax weighted average cost of the capital on the basis of normative debt: equity ratio (70:30) and is given by Eqn. 3.10.

a. For the loan component, the interest rate considered is 12.76%.
b. For the equity component, the Rate of Return on Equity ($RROE_{PV}$) is considered at a post-tax ROE of 16%.

$$DR_{PV} = \{(LP_{PV} \times RIOL_{PV} \times (1 - AT_{PV})\} + \{EP_{PV} \times RROE_{PV}\} \quad (3.10)$$

where LP_{PV} is the percentage at which a loan is obtained for a PV project, AT_{PV} is the Applicable Tax in % (current value is 34.61%), EP_{PV} is the Equity Percentage and $RIOL_{PV}$ is the Rate of Interest on Loan Capital. A realistic discount rate can also be determined using the Weighted Average Cost of Capital (WACC) which represents the weighted mix of debt and equity costs for the investor [21]. The WACC is considered as the overall combined effect of the cost of debt, cost of equity, share of CAPEX, and the corporate tax rate [106] and has a very high influence on LCOE.

The discount rate considered in India as per CERC comes out to be 10.64%.

iii. **Annual Working Capital (AWC_{PV}):** As per RE tariff regulations, the annual working capital requirements of the solar PV projects are given by Eqn. 3.11.

$$AWC_{PV} = MOM_{PV} + 2\,(REC_{PV}) + MS_{PV} \quad (3.11)$$

where MOM_{PV} are Monthly O & M expenses, REC_{PV} is Receivable Energy Charge and MS_{PV} is Maintenance Spares (15% of O&M expenses).

iv. **Interest on Working Capital (IWC_{PV}):** The interest on working capital is an interest rate equivalent to the average base rate prevalent during the first six months of the previous year plus 350 basis points for the period. In India, the average base rate of the State Bank of India is considered. During the first six months of FY 2015-16, the base rate was 9.76% that has resulted in interest on working capital @13.26% for FY 2016-17. Therefore, the expression for calculating interest on working capital is given by Eqn. 3.12.

$$IWC_{PV} = 0.1326 \times AWC_{PV} \quad (3.12)$$

The project details are placed at Appendix-I (Table I.1) and the sheet for the determination of solar tariff for the year 2016-17 is placed at Appendix-II (Table II.1). It can be observed from Appendix-II (Table II.1) that the total cost of generation is varying from Rs. 7.09 per unit to Rs. 3.7 per unit. The calculated discount rate is Rs. 10.64% that resulted in levelized tariff of Rs 5.68 per unit for 25 years.

3.4 Conventional Thermal Tariff Vs Solar Tariff

Tariffs from thermal energy are plant-dependent and mainly depend on coal quality and its mix, thus to get an idea of the Power Purchase Cost (PPC) of thermal energy on a year-to-year basis, conventional thermal tariff has been taken from the tariff of National Thermal Power Corporation Limited (NTPC Limited) tariff rates [21]. NTPC Limited is the country's largest power-generating company with a share of 17% of the installed capacity, NTPC currently contributes 24% of the total electricity produced in India. Fig. 3.3 shows the variation of conventional thermal tariff vis-à-vis solar PV plant tariff [100] [102] [103] [101]. Till 2017 rates from CERC levelized cost of solar PV were taken and for a period after 2017, rates have been obtained from rates of competitive bidding.

When the National Solar Mission was declared in the year 2010, the cost of solar electricity was Rs.17 per unit relative to the Rs.2.00 per unit in year 2020. This breakthrough cost-cutting was made possible by competitive tariff-based bidding activities conducted by India's Solar Energy Cooperation (SECI), central and state governments. From Fig. 3.3 [107], it can be observed that power purchase costs have been steadily increasing from 2011 to 2022 for thermal tariff.

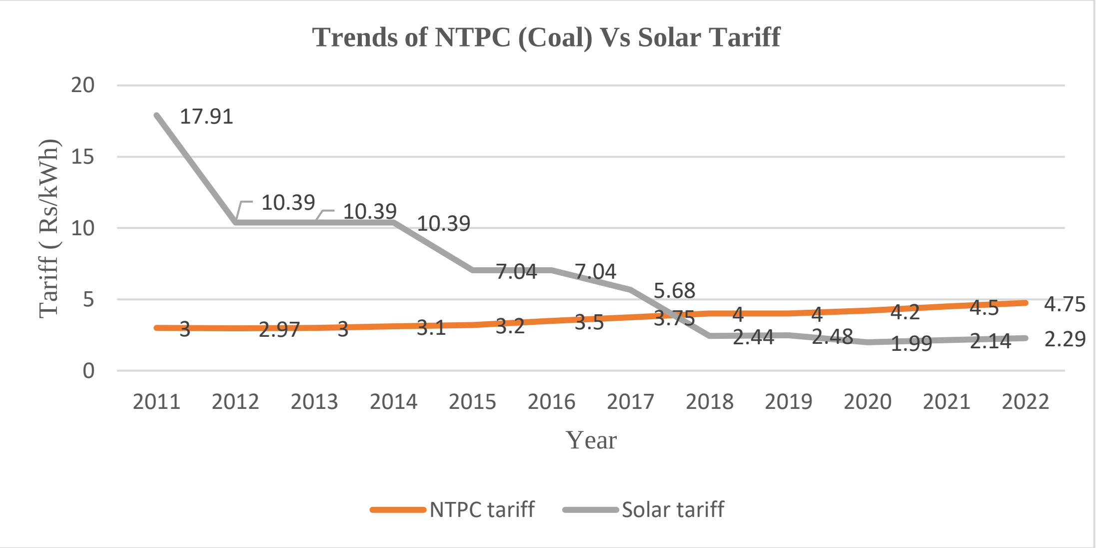

Fig. 3.3 Variation of PPC Without RE Vis-À-Vis Generic CERC Levelized Cost

3.5 Bridging the Tariff Gap

Various direct and indirect factors have contributed to bridging the tariff gap i.e. to bring solar PV LCOE at par with PPC of thermal power [108] [109] [110]

[111]. It is evident from Fig. 3.3 [107] [100] [102] [103] [101] that initially in the year 2011, the gap between generic solar tariff and PPC without RE was around Rs 15 which narrowed to Rs. 2.46 in the year 2022.

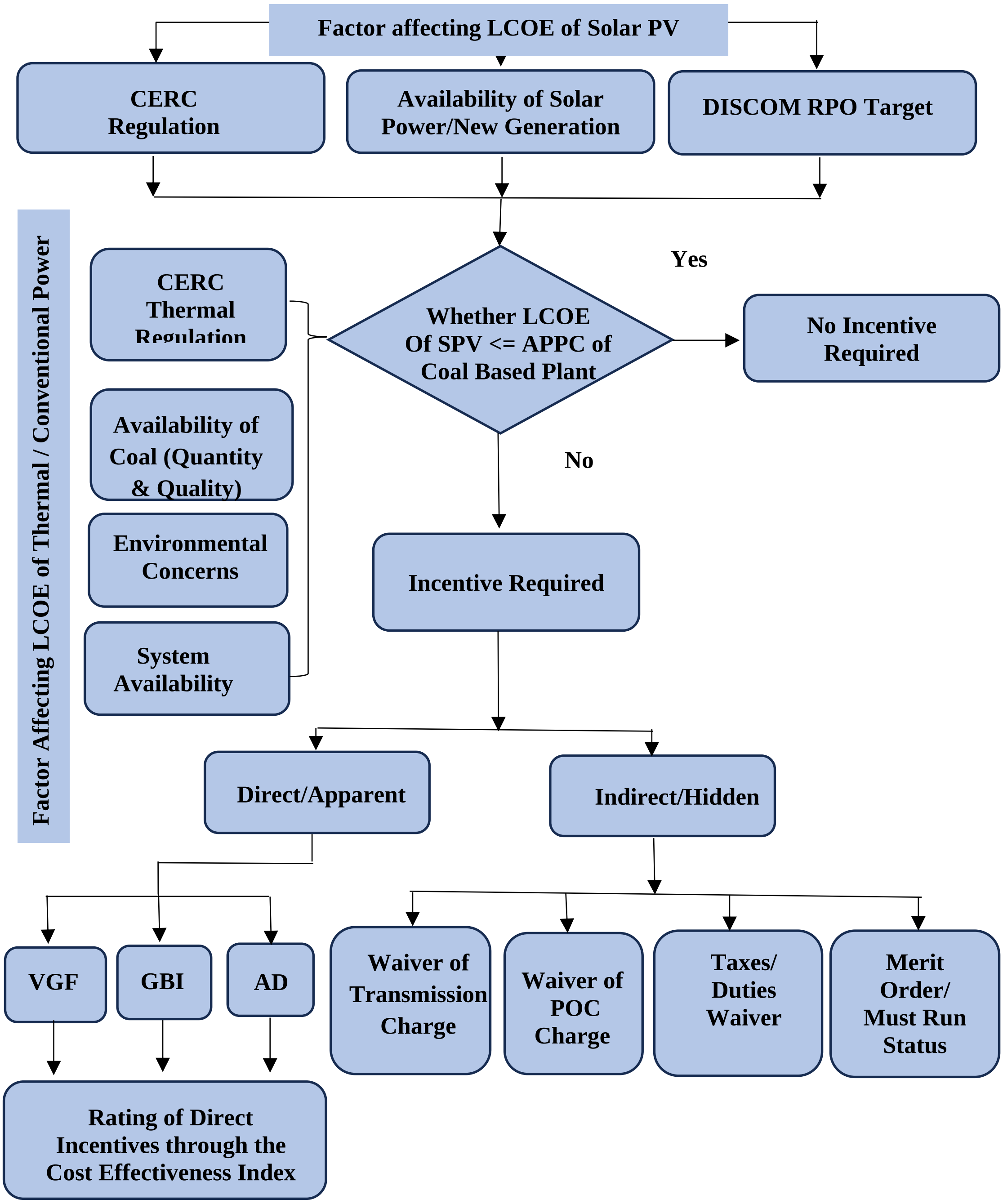

Fig. 3.4 Flow Chart of the Methodology Adopted (APPC= Average Power Purchase Cost)

To bridge the tariff gap, incentivize solar power generation, and promote the setting up of a large number of solar power projects, policymakers have considered various incentives. The various incentives available have been categorized into direct/apparent benefits and indirect/hidden benefits. The flowchart of the methodology adopted for the study is shown in Fig. 3.4:

The key assumptions taken during the analysis are:

i. It has been assumed that the GBI is distributed equally at a rate of Rs. 2 per kWh for a generation of more than 1100 units in accordance with disbursal criteria notified in the solar policy of the Government of National Capital Territory of Delhi (GNCTD) through its Department of Power [112].

ii. Disbursal of AD benefit @ 40% for 1st year and @ 80% for 2nd year onwards has been considered in accordance with the Ministry of New and Renewable Energy guidelines.

iii. To have maximum impact on the tariff VGF ceiling of Rs. 94 lakh/MW has been considered and it is assumed that the complete amount is disbursed in the initial year.

iv. To obtain the Power Purchase Cost (PPC) of thermal energy on a year-to-year basis, the PPC of NTPC Limited has been taken. The genesis of the assumption is that NTPC Limited, the country's largest power-generating company, with a share of 17% of the installed capacity, NTPC currently contributes 24% of the total electricity produced in India [113].

v. The rating of various direct incentives and schemes in the cost-effectiveness index is indicative and depends on the values of parameters taken in analysis and are thus case-specific e.g., if the rate of depreciation, GBI, or the amount of initial VGF are changed, the results will be different.

vi. The value of the Capacity Utilization Factor is taken as 19% and the life of the plant is taken as 25 years as per CERC guidelines [101].

The following sections will discuss in detail the effect of various direct and indirect factors in bridging the tariff gap.

3.5.1 Effect of Direct Factors in Bridging the Tariff Gap

The various direct factors that contributed to bridging the tariff gap are given below:

i. Viability Gap Funding Scheme

Viability Gap Funding (VGF) scheme is one of the most popular schemes in the early stage of the promotion of PV plants. It is an economic instrument used by any government with the motive of supporting projects that are economically justified but are not financially viable. In the case of renewable energy projects, "VGF" is the fraction of capital cost required to achieve the target LCOE. VGF is granted by the government through the reverse bidding process. The lowest bidder of the VGF amount is required to deliver output at a predefined cost. The scheme does not focus on long-term performance but rather is a direct financial incentive that requires upfront payments so it helps in mitigating risk chances of lenders, reduction in tariff, and overall promotion of the sector. VGF payments are generally spread over a few initial periods of project (say 6 years), with an aim to elicit project performance. VGF amounts are decided through a competitive process, and the payments are not specifically linked to the amount of power generated. However, to monitor project development, VGF amounts are generally released in three tranches as follows:

i. 25% amount at the time of delivery of 50% (at least) of the major equipment at the site.
ii. 50% amount on successful commissioning (full capacity) of the plant.
iii. 25% amount after one year of operation meeting requirements of generation.

The effect of the VGF scheme on LCOE has been shown in Fig. 3.5. VGF ceiling of Rs. 94 lakh/MW has been considered and it is assumed that the complete amount is disbursed in the initial year itself so that it has maximum impact on tariff. VGF of Rs. 94 lakhs have reduced LCOE from Rs. 5.68/unit to Rs. 5.43/unit. However, it can be argued that the same amount could be disbursed periodically based on performance or milestones achieved but then, the overall impact on the tariff would be lesser.

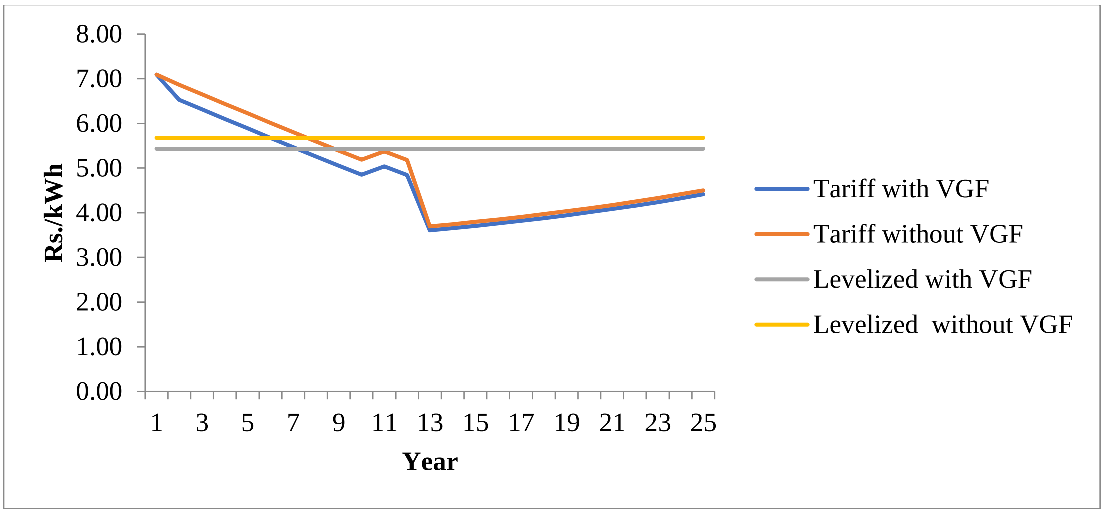

Fig. 3.5 Effect of VGF on Solar Tariff.

ii. Generation-Based Incentive Scheme

Generation-based incentives (GBI) are provided to support small-grid solar power projects connected to the distribution network under the solar GBI scheme [114]. GBI scheme aims to reduce payback time and increase solar PV adoption. GBI is an output generation-based & performance-linked incentive scheme. The disbursal depends on the number of units generated over and above a minimum value. GBI incentives ensure minimum quality in installations. Under the scheme for GBI in solar energy, a fixed amount per unit of energy generated is provided to support small-grid solar power projects connected to the distribution grid below 33 kV. This financial incentive is not upfront and does not burden the government like the VGF fund. Since this incentive is linked with the generation output of the plant, it encourages proper operation of the plant and promotes the use of quality solar generation equipment.

GBI is basically a tail-end incentive scheme that provides tariff comfort and therefore offers a meagre financial advantage. However, it can be designed in such a way that if the GBI amount is paid to the concerned utility then it will motivate the utility to buy more and more solar power and also help them to make timely payments to generators. GBI payments are paid on a first-come-first-served basis until the yearly funds earmarked for GBI run out. The instrument of GBI can also be used as a payment security mechanism. In case a consumer fails to make payment to the vendor, a Generation-Based Incentive may be passed on to the vendor.

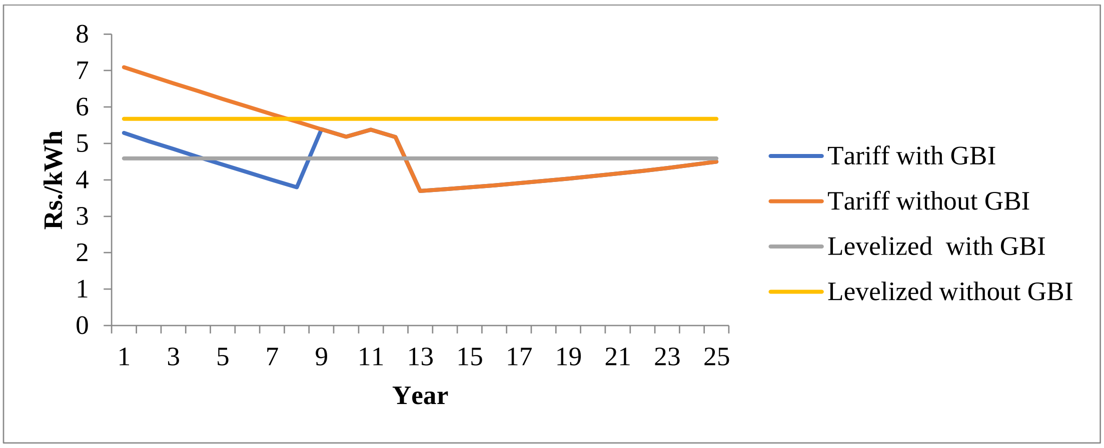

Fig. 3.6 Effect of GBI on Solar Tariff.

The effect of the GBI scheme on LCOE has been shown in Fig. 3.6. GBI benefit @ Rs. 2 per kWh for a generation of more than 1100 units has been considered. The maximum limit of generation for GBI disbursement has been capped at 1500 units. The GBI benefit is applicable for the first 8 years of operation. Taking the base case of the CERC generic tariff for the year 2016-17, the GBI benefit has resulted in a decreasing LCOE to Rs. 4.59 from the base LCOE of Rs. 5.68.

iii. Accelerated Depreciation

In AD, the depreciation is deliberately allowed more in the initial years of its useful life (say 40% in the 1st year), as the vendor has to pay lesser taxes if the asset gets depreciated earlier. Thus, accelerated depreciation accounts for major relief in the upfront cost of PV by providing a tax break in the first year of operation. This method doesn't have any substantial or direct impact on the government although the government loses some money in terms of taxes. Although this method has the ability to attract large investors, the drawback of this method is that does not consider the operational efficiency of the plant. However, it can be designed to link with the plant's performance (e.g., a bank guarantee may be deposited by the vendor who wants to avail AD benefit, which can be released periodically on a minimum performance basis annually).

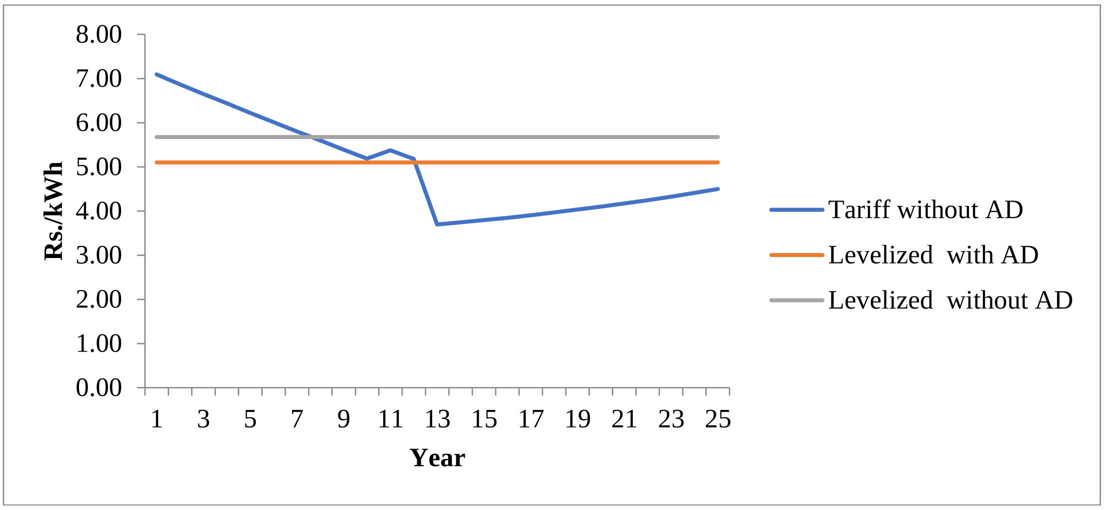

Fig. 3.7 Effect of AD on Solar Tariff.

The effect of AD on LCOE has been shown in Fig. 3.7. AD benefit @ 40% for 1st year and @ 80% for 2nd year onwards has been considered. AD benefit has resulted in a decreasing LCOE to Rs. 5.14 from the base LCOE of Rs. 5.68.

iv. Combined Effect of AD, VGF, and GBI Benefit on Solar Tariff

The effect of already discussed benefits viz. AD, GBI, and VGF on base LCOE are analysed and are shown in Fig. 3.8 and it can be observed that the levelized tariff after considering the combined effect of VGF, GBI, and AD has reduced to Rs. 3.81/- against baseline levelized tariff of Rs. 5.68/-.

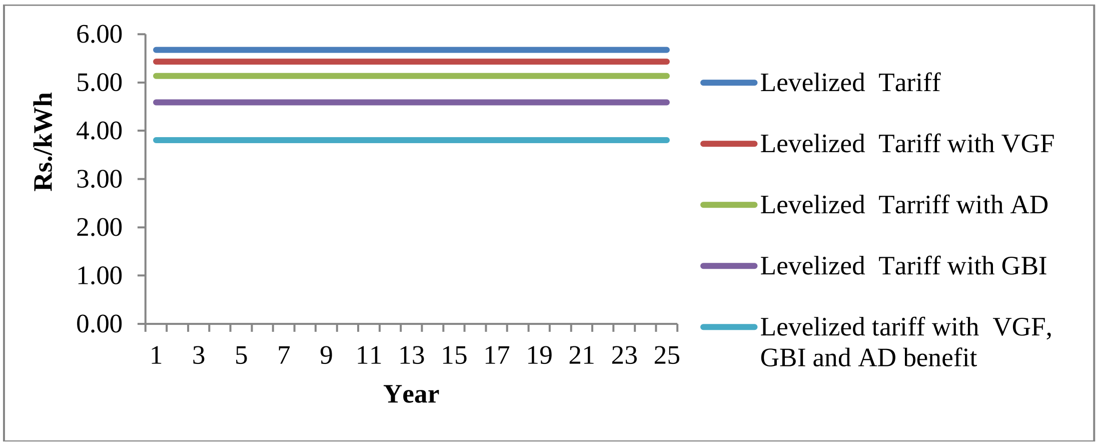

Fig. 3.8 Effect of AD, VGF and GBI on Solar Tariff.

3.5.2 Contribution of Indirect Factors in Bridging the Tariff Gap

Besides various direct factors explained above, there are some indirect factors that have given impetus to the solar sector and helped in bringing solar PV

LCOE to par with the PPC of thermal power. The various hidden alternatives available are waiver of transmission losses and point of connection charges, import duty waiver on imported PV modules, exclusion of solar generation from merit order dispatch/ must-run status, and various government policies especially the announcement of NSM. The following sections will explain some of these alternatives that have resulted in a further decrease in solar tariffs.

i. Waiver of Transmission Losses and Point of Connection (PoC) Charges

Ministry of Power, GoI has been promoting the solar PV sector by incentivizing and thereby making the cost of electricity from these plants at par with that of conventional thermal generation plants, which are still the base load plants. Table 3.3 shows some of the latest discovered rates of electricity from PV parks [115].

Table 3.3 Recent Rates Discovered Through Competitive Bidding in India [115]

Solar Park/Plant	Capacity (MWp)	Levelized Tariff for 25 years (Rs. / kWh)
Rewa PV	750	3.30 (Rs. 2.97 for First Year)
Bhadla PV	420	4.34
Pavagada PV	500	4.78

If we take a closer look at tariff rates discovered through competitive bidding for the solar park, it can be seen that the levelized tariff in year 2017 came down to as low as Rs. 2.97/- for the Rewa plant for the first year and a levelized tariff of Rs. 3.30/- for 25 years. The solar generation from Rewa Solar Park commissioned in 2020, Madhya Pradesh is injected into Delhi (withdrawal point) for utilisation to the Delhi Metro Rail Corporation (DMRC) network.

The Power System Operation Corporation Limited (POSOCO), GoI enterprise has issued an amendment to the regulation for "Sharing of Inter-State Transmission Charges and Losses" to waive ISTS charges and losses. In absence of this amendment, DMRC may have to bear an additional nearly 91 paise per unit cost duty to ISTS charges and losses that would have resulted in an increase of tariff from Rs. 3.30 per unit to nearly to Rs. 4.21 per unit in year 2017. Thus, it can be said that the waiver of ISTS charges and losses played a key role in reducing the tariff rates.

ii. Exclusion from Merit Order Dispatch/ Must Run Status

Solar power projects enjoy must-run status i.e., DISCOMs must procure electricity from solar power plants even if that results in partial scheduling or complete shutdown of conventional thermal power plants. Since the CUF of a typical solar PV project in India is only 15-19%, if scheduling is capped for these plants on the basis of merit, the CUF shall go even down and shall increase LCOE as total annual generation will reduce. Thus, by providing an exclusion from merit order dispatch, it is ensured that rates of solar generation are kept under check.

iii. Government Policies

Government policies have played a crucial role in bringing down solar tariffs. The role of GoI commitment under JNNSM, Panchamrit, Performance Linked Incentive (PLI) schemes etc is worth noting. At the time of the launch of NSM in 2010, the country had only 160 MW of solar generation and that has increased to 85 GW in June 2024. Several schemes namely Central Public Sector Undertakings (CPSUs), rooftop, canal bank/canal top, PM Surya Ghar, PM -KUSUM etc. under NSM are initiated by MNRE. The effect of the government push can be gauged from the fact that the tariff in one recent bid came down to Rs. 2.00/- per unit, whereas that approved by the CERC for solar power was about Rs. 15.39 per unit in 2010-11 when the mission was launched. Apart from the National Solar Mission (NSM) other government schemes such as Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) and the solar park scheme have contributed immensely to bringing solar tariffs down.

3.6 Cost-Effectiveness Index

One of the possible ways to rate the direct incentive scheme as per some criteria is through the cost-effectiveness index that is basically the ratio of reduction of cost to consumers and the total cost (both direct and indirect) to government as can be seen in the last column of Table 3.4.

Table 3.4 Cost-Effectiveness Index Considering Direct Factors.

Calculation of Cost-Effectiveness Index for AD, GBI and VGF								
1000 kW Solar Plant (a)	**Capital Expenditure (CAPEX) (b)**	**LCOE (c)**	**Reduction in LCOE from Baseline (d)**	**Cost Reduction for the Consumer over the Lifetime (25 yrs.) (e)**	**Direct Cost to Govt. (f)**	**Indirect Cost to Govt. (Income Tax Loss due to AD Benefit) (g)**	**Total Cost to Govt. (Direct & Indirect) (h)**	**Cost-Effectiveness Index (i)**
Units	Rs. Lakh	Rs. / kWh	Rs. / kWh	Rs. lakh (Net Present Value)	Rs. lakh (Net Present Value)	Rs. lakh (Net Present Value)	Rs. lakh (Net Present Value)	Dimensionless
Baseline	530.02	5.68	-	-	-	-	-	-
AD	530.02	5.14	0.54	224.48	0.00	154.82	154.82	1.45
GBI- 2 Yrs.	530.02	5.32	0.36	147.82	57.00	0	57.00	2.59
GBI- 8 Yrs.	530.02	4.59	1.09	452.08	173.03	0	173.03	2.61
VGF	530.02	5.43	0.24	101.11	94.00	0	94.00	1.08

The LCOE (column c) is derived from Appendix- II (Table II.2) for respective schemes. Reduction in LCOE (column d) is considered over the baseline LCOE of Rs. 5.68. The cost reduction for consumers over a period of 25 years (column e) is considered. The direct cost to the government is the net present value of the amount disbursed in the GBI and VGF schemes while the tax loss due to the provision of AD benefit will comprise indirect cost to the government (columns f & g). The total cost to the government will then be the sum of direct and indirect costs (column h). The financial efficacy of a particular policy option will depend on the value of the ratio (the higher the better).

From the study, it can be concluded that GBI is scoring high among VGF, GBI, and AD. Initially, we have taken the case of disbursal of GBI for the initial 8 years but even if the analysis is carried out for a more practical duration of the initial 2 years, the effect on the cost-effectiveness index is negligible. The analysis given above mainly depends on the values of parameters taken in the analysis and are thus case-specific e.g., if the rate of depreciation or the amount of initial VGF is changed, the results will be different.

3.7 Economics of Solar Energy: International Scenario

With the solar market becoming more and more competitive and subsidy-independent, financiers are becoming more comfortable with solar market risks. India and China have a strong and sophisticated domestic financing ecosystem, capable of meeting their investment requirements while countries such as Kenya or Myanmar do not have such a strong domestic financing ecosystem therefore, they rely more on international financing for scaling up their solar growth. Germany, the USA, and China relied predominantly on domestic financing; India is moving from international to domestic financing.

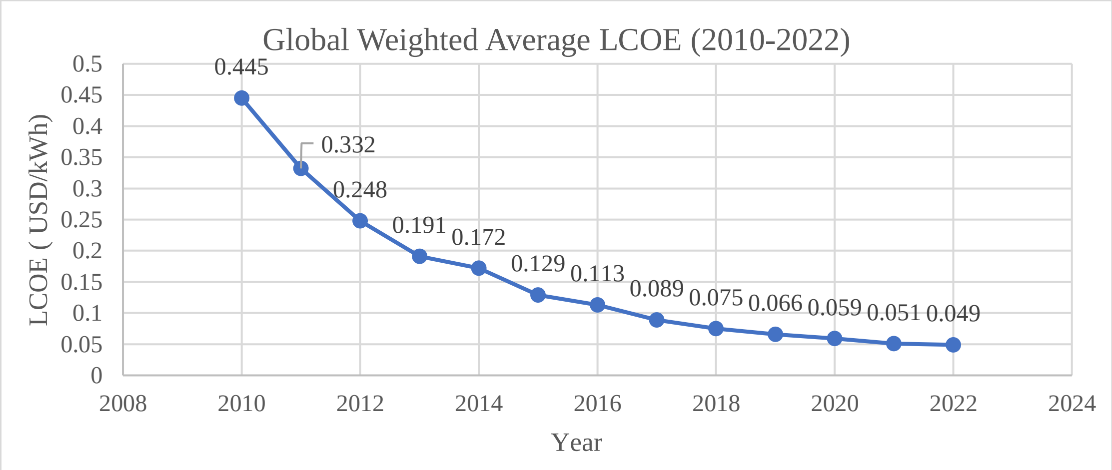

Fig. 3.9 Trends of Global Weighted Average LCOE of Utility-Scale Photovoltaic (PV) Plants

The solar market in countries such as Kenya, Nigeria, Ethiopia, and Myanmar are based on a higher share of international finance and in Mexico domestic commercial banks provide most of the debt to both utility-scale and rooftop solar projects and a large part of the equity financing is provided from international developers [116]. The global weighted average levelized cost of electricity of utility-scale photovoltaic (PV) plants declined by 89% between 2010 and 2022, from USD 0.445/kilowatt hour (kWh) to USD 0.049/kWh in 2022, as shown in Fig. 3.9.

Depending on the kind, the cost of crystalline silicon modules marketed in Europe decreased by 88% to 94% between December 2009 and December 2022. The weighted average cost decrease was almost 91% during the same period. The country average for the total installed costs including hardware, installation and soft costs (financing, incentives etc.) of utility-scale solar PV ranged from a low of USD 640/kW in India to a high of USD 1905/kW in Japan. In 2016, BoS expenses (excluding inverters) accounted for almost 50% of the overall system expenses while in 2022 its percentage has risen to 63%. The BoS percentage of total installation costs in 2022 varied between various nations from 53% in Estonia to 75% in Ireland.

Module prices were the single largest contributor to the LCOE drop between 2016 and 2022. The other major single contributor to this is a decline in BoS hardware cost. Among nations, the lowest weighted average LCOE in 2022 could be observed in China and India. Between 2010 and 2022, costs in China declined by 89%, while in India they declined by 90% to reach USD 0.037/kWh. Major LCOE reductions occurred in the top markets in the UAE and Saudi Arabia, where the impact of lower total installed costs is supported by excellent solar resources [117].

3.8 Analysis and Discussion

In this study, the role of various direct potential incentives like VGF, AD, and GBI and indirect benefits like waiver of transmission losses and point of connection charges, exclusion of solar generation from merit order dispatch/must-run status, and various government policies etc. in bridging the tariff gap between solar and conventional power have been analysed. The summary of results achieved after consideration of various direct incentives is given in Appendix II (Table II.2). The study also proposed a criterion to rate the direct incentive scheme through the cost-effectiveness index.

It has been felt that on the one hand, the solar industry is facing the challenge of bringing LCOE down to keep consumers and discoms interested, and on the other hand, it has to take steps to safeguard the interest of investors. LCOE alone is not the major factor in the adoption of solar PV power. Financial indicators such as the Internal Rate of Return (IRR), Net Present Value (NPV), and ROE are the basic indicators of the profitability of the project. Distribution businesses in India were circumspect initially about adopting solar PV due to their financial strain. In the past few years, the Indian government has targeted the right tool of directly subsidizing the technology through VGF, AD, GBI, etc. to bring it at par with conventional generation tariffs. This has led to a decrease in the LCOE of the solar PV projects for the consumer and thus paved the way for its faster adoption. CERC provided a high rate of return on equity of 20% per annum for the first 10 years and 24% per annum from the 11^{th} year onwards for solar PV which is one of the highest in the sector. A high rate of ROE not only means more profitability for the investor but it also brings more investment in the sector. Moreover, with enhanced installation, more module manufacturers have entered the fray resulting in a substantial reduction of module cost and with the reduction of module cost, LCOE of the projects has come down drastically and, direct and indirect government subsidies are resulting in over-subsidizing the projects.

In the face of rapid advancements in solar technology, which led to reduced production costs and a surplus of energy supply, the government introduced an innovative "auction" system. The Central Electricity Regulatory Commission has decided to determine tariffs on a project-by-project basis instead of a generic tariff for solar PV plants. Under this system, renewable energy prosumers participated by bidding to establish tariff rates for selling their electricity. This initiative yielded remarkable results, driving down tariff rates by nearly 50% compared to the previous feed-in tariff system. Additionally, the government waived Inter State Transmission System charges (ISTS) for electricity generated from solar and wind projects up to a specified commissioning date, promoting further adoption of clean energy sources. For solar and wind power to be commissioned up to 30.06.2025, ISTS charges have been waived off. While tariff decisions by regulatory commissions witnessed a substantial decline, transitioning to a project-specific approach, the broader energy landscape is gradually evolving. It appears that the tariffs of solar PV plants have reached their Nadir. As we move towards more dynamic market pricing, the withdrawal of certain support measures highlights the maturation of the solar industry, underscoring a pivotal juncture in the journey towards sustainable and market-driven energy solutions. Given solar energy’s sustainability and cost-efficiency, its inclusiveness and scalability are going to be the fulcrum on which its wider acceptance as a source of power is going to be based.

Based on this study, it is recommended that as LCOE is coming down, the government may think of pulling back some of the incentive schemes such as VGF, AD, and GBI and let the PV projects compete in the market without any kind of economic stimuli. Further, some hidden incentive schemes such as waiver of inter and/or intrastate transmission charges and losses, waiver of import duty on modules, the bestowment of must-run status or exemption from Merit Order Dispatch (MOD) are still needed for the sustenance of solar PV plants.

3.9 Concluding Remarks

In the chapter, various direct incentive schemes affecting solar LCOE have been compared based on certain assumptions, and it has been observed from the cost-effectiveness index matrix that GBI scores high among VGF, GBI, and AD. Despite the fact that results are case-specific as the decrease in value of LCOE from the base value of Rs. 5.68/kWh mainly depends on the initial value of VGF, rate & duration of disbursal of GBI, and depreciation rates. The results strongly indicate the role of various incentives and government schemes in narrowing the tariff gap between LCOE of solar PV and conventional thermal tariff.

CHAPTER 4

PERFORMANCE EVALUATION OF A GRID-CONNECTED PV PLANT INTEGRATED WITH BATTERY ENERGY STORAGE SYSTEM

4.1. Introduction

World over various countries are becoming more and more interested in grid-connected photovoltaic (PV) systems as a way to provide an alternative to traditional fossil fuel power. IEC 61724 provides the required standards for assessing the performance of grid-connected systems. The two configurations of SPV plants viz. grid-tied and grid-interactive are more popular than off-grid, particularly in medium and large capacity. Large-scale utility solar photovoltaic plants are usually grid-tied, comprising of PV arrays, inverter, grid and no battery. They require a stable grid to be functional and the power flow is unidirectional i.e., from PV to grid through inverter. On the other hand, grid-interactive PV systems allow bidirectional power flow with reference to the inverter. The present study analyses the performance of a grid-connected SPV system located in Delhi based on performance ratio and capacity utilisation factor as major performance indicators. The analysis of the already operational grid-connected solar PV plant located at Indraprastha Thermal Power Station for Delhi Secretariat building is done with the following objectives:

i. To compare and analyse actual performance data obtained from the monitored SCADA system for the study period.
ii. Determination of the optimal size of the BESS that maximizes the annual benefits to the building when the BESS and distributed energy resources like solar PV are used for peak load shaving under variable electricity energy pricing dynamics.

The comparative outcomes of the present study will provide input for government authorities, policymakers, and other stakeholders like investors, project developers, etc. to develop regulations and policies for the promotion of battery storage for such types of installations wherein distributed sources of energy and Battery Energy Storage System (BESS) are being used in coordination.

4.2. Project Details

To reduce the dependence on fossil fuel-based energy sources and to prevent environmental degradation, it was decided that the Delhi secretariat building in Delhi be designed as a green building having a solar photovoltaic power plant to meet all its energy requirements. The climatic condition of Delhi is characterized by high variation between summer and winter temperatures on account of its proximity to the Himalayas in the North and the Thar Desert in the West. A detailed examination of the performance of solar photovoltaic systems in such high variation of climatic conditions of Delhi provides insight into the actual operation of the plant and suggests corrective actions for system planning and future requirements.

A 2MWp solar photovoltaic power plant was installed on the vacant land of the dismantled Indraprastha Thermal Power Station located near the Delhi Secretariat building. Delhi Secretariat building is Y-shaped with Ten stories' also known as Delhi Sachivalya or the Players building. The building was originally built for the housing of athletes of the 1982 Asian Games and then renovated to accommodate important Delhi government offices including that of Chief Minister and Cabinet Ministers. Delhi secretariat building has a contract demand of 3000 kVA and therefore, the design of the solar PV power plant of 2 MW capacity was proposed that has to be installed in phases. Due to the scarcity and cost of the land in Delhi, it was decided to install a solar PV plant on the vacant land of the dismantled Indraprastha Thermal Power Station (near the Delhi Secretariat building). This solar power plant will supply power directly to the Delhi Secretariat. Delhi Secretariat will consume this power and will run completely on solar power for most of the time. Out of the proposed 2 MW capacity, 1 MW capacity was installed and operational since 24th October 2015, and the remaining 1 MW was installed in 2018. The power so generated is being fed to the Delhi secretariat building through the radial feeder. The coordinates of the designated area are 28.62 degrees N and 77.25 degrees E. The tariff to be paid to the successful solar power developer is fixed at Rs.4.50 per kWh, for the entire period of 25 years of the Power Purchase Agreement (PPA). The land for the project having an estimated area of 17 Acres, was made available to the Project developer on an 'as-is-where-is basis' without any financial assistance. The complete design aspect of 2 MW solar PV plants is given in subsequent sections.

It was initially believed that this type of arrangement in which the grid provides limitless storage and PV generated electricity is supplied directly to the grid would be sufficient hence no provision was kept for battery storage operations. However, with the advent of economical BESS at large-scale levels, it was proposed to install a battery storage plant as a pilot project. In this study, two methodologies are analysed and comparative analysis is represented for both Time of Day (ToD) and flat tariff regimes. In case A the analysis is made considering that there is no availability of BESS and is considered a reference case. In case B it is considered that whenever there is excess solar energy after self-consumption, it will be stored in the battery for usage in subsequent load cycles. Given the load profile of the building, the condition of surplus solar energy will happen during weekends and holidays and summer months offers an excellent opportunity for saving through battery storage.

4.2.1 System Description

A solar PV grid-connected system consists of a PV array, power conditioning unit, inverters, power evacuation equipment, and a data monitoring system. Fig. 4.1 shows block diagram of the SPV plant for the Delhi secretariat building. The output of the solar plant is connected to the Delhi secretariat building which is located at a distance of 2 Km from the plant through an 11 kV, XLPE underground cable.

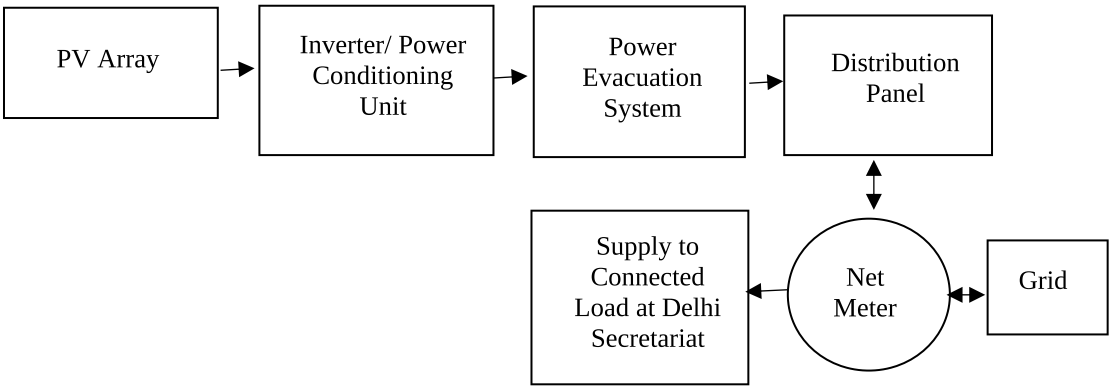

Fig. 4.1 Block Diagram of SPV Plant for Delhi Secretariat Building

Fig. 4.2 shows a view of the solar PV plant with the Delhi secretariat building in the background. Though the connected load of the Delhi secretariat building is more than the installed capacity of the plant i.e., 2 MWp, however during weekends and holidays, the system supplies excess power beyond consumption levels to the utility grid.

Fig. 4.2 Arial View of the Solar PV Plant with Delhi Secretariat Building in Background

i. PV Array

Multi crystalline silicon modules of WAREE make, series WS-310 having a maximum power of 310 W are used. The open circuit voltage (Voc) and short circuit current, (Isc) ratings of each module are 45.20V and 9.14 A respectively. Each module has 72 cells and module efficiency is 15.98 %. Modules are connected to inverter through 24 inputs combiner box. Strings of 20 modules in series are connected in parallel to achieve combine capacity of 2MW.

ii. Tilt Angle

The tilt angle is considered according to the geographical location of the plant and is normally kept the same as the latitude of the location to get maximum solar radiation [118]. This solar plant uses manual seasonal tilt technology to absorb more solar radiation and extract more power output. The SPV modules are oriented with variable seasonal inclination. From October to March as it is winter season, tilt is kept at higher values of 30°, and for the rest of months, as it is summer season and more radiation is absorbed, the tilt angle is kept as low as 10°.

iii. Power Electronics Interface

The output voltage of PV is DC while the loads are mostly AC. To get the output voltage of the desired magnitude and frequency, the output of PV is fed to the AC load through power conditioning units and inverters. To provide maximum output from the SPV system, the power conditioning unit has been provided with an inbuilt maximum power point tracking facility. Also, the inverter size should be 25-30 % higher than total requirement. Hence, considering the design requirement of the plant, three 750 kW grid-connected photovoltaic transformer-less inverters of Toshiba Mitsubishi-Electric Industrial System Corporations (TMIEC) are used. The inverters employ Insulated Gate Bipolar Transistor (IGBT) switches and their output voltage will automatically be synchronized with grid AC voltage as long as the grid voltage is within a tolerable frequency and voltage range.

iv. Power Evacuation and Metering

The SPV output from three inverters is fed to the inverter substation through a 2000 kVA,11kV/0.380-0.380-0.380kV transformer. The vector group of the transformer is Dy11y11y11 and the cooling is ONAN. The Inverter substation located at the site has a vacuum circuit breaker of capacity 12kV, 630A, and 21kA for 3sec. Metering of evacuated power is done using an Availability-Based Tariff (ABT) main and check meter along with Current Transformers (CT) and Potential Transformers (PT) installed in the metering panel. A two km long 11 kV, 3C x 185 sq. mm XLPE insulated aluminium armoured cable runs from the solar PV plant to the Delhi secretariat substation for power evacuation.

v. SCADA/ Data Monitoring System

Data acquisition is carried by the Sunny sensor box; it has an integrated irradiation sensor and an external module temperature sensor. In addition, there is an option of connecting a sensor for ambient temperature and/or an anemometer to the Sunny sensor box. The Sunny Sensor box is integrated into an RS485 communication bus. A maximum of 50 devices are allowed onto an RS485 bus (including the Sunny Sensor Box).

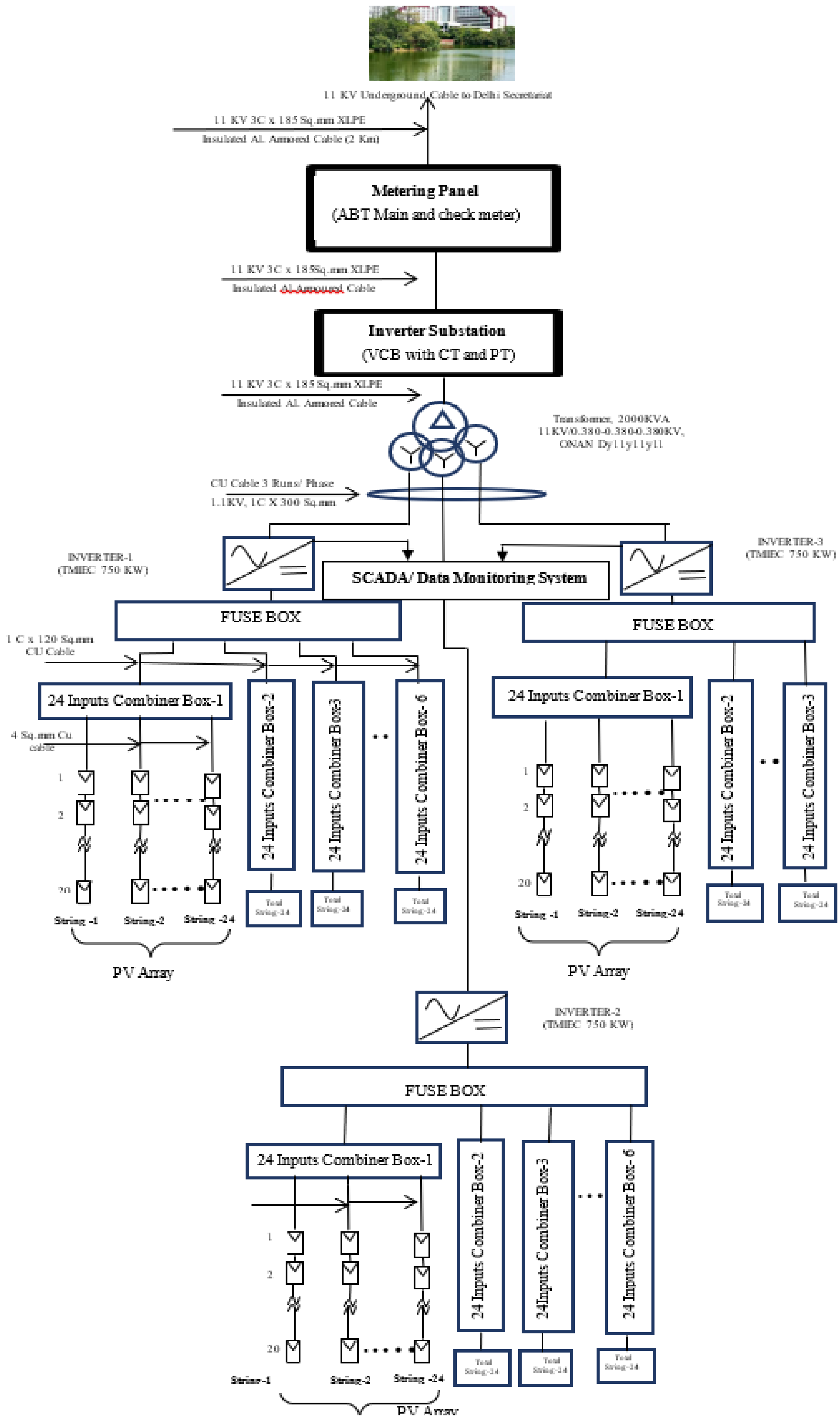

Fig. 4.3 Connection Diagram of 2MW Solar PV Plant for Delhi Secretariat Building

The RS485 power injector provides the sunny sensor box with electricity and must be mounted indoors. The sensor box sends the sensor data to the SMA communication devices via an RS485 interface. The Supervisory Control and Data Acquisition (SCADA) server retrieves the information and updates graphical screens. Solar irradiance, voltage, current, and power at the input and output of each inverter as well as wind speed, module, and ambient temperature are recorded by the data logger at an interval of every 15 minutes. The connection diagram of the solar PV plant for the Delhi secretariat building is shown in Fig. 4.3.

4.2.2 Performance Parameters

Accurate and consistent evaluations of photovoltaic (PV) system performance are key to the development of the PV industry. For end customers these performance parameters are vital tools for evaluating PV components in terms of product quality to guide future decision-making. To analyse the performance of a grid-connected SPV system, the performance parameters are being developed by the International Energy Agency (IEA) [119]. These performance parameters include:

i. Total Energy Generated by the System: The total daily energy ($E_{AC,\,d}$) is the sum of all instantaneous measured values of energy ($E_{AC,\,t}$) recorded by the PV system during 24 hours and is given by Eqn. 4.1 as:

$$E_{AC,\,d} = \sum_{t=1}^{24} E\,(_{AC,\,t}) \tag{4.1}$$

The monthly energy generated ($E_{AC,\,m}$) is the sum of all daily energy values recorded in a month and is given by Eqn. 4.2.

$$E_{AC,\,m} = \sum_{d=1}^{N} E\,(_{AC,\,d}) \tag{4.2}$$

Where N is the number of days in the month.

ii. Final Yield (Y_F): Final Yield (Y_F) is defined as the ratio of total energy generated by the PV system in a given period (day, month, or year) to the rated installed output power of the PV system [119]. It represents the number of hours that the PV array would need to operate at its rated power to provide the same energy and therefore is a tool to make the comparison of solar PV systems of different sizes and is given by Eqn. 4.3.

$$Y_F = E_{AC}/P_{PV,\,Rated} \tag{4.3}$$

Where E_{AC} is the total energy generated by the PV system in a given period and P_{PV} is the rated installed capacity of the plant.

iii. Reference Yield (Y_R): Reference Yield is the ratio of total in-plane irradiance (H_{it}) to the PV's reference irradiance (G) and is given by Eqn. 4.4-4.5 [120]. It represents the energy obtained under ideal conditions. The reference yield (Y_R) represents the number of peak sunshine hours if G is equal to 1 kW/m^2. It is the function of the location, the orientation of the PV array, and the weather variation throughout the year.

$$Y_R = H_t/G \quad (4.4)$$

$$Y_R = (kWh/m^2) / 1\ kW/m^2 \quad (4.5)$$

iv. **Capacity Utilization factor (CUF):** The capacity utilization factor, given by Eqn. 4.6 is defined as the ratio of annual energy output to the annual energy the PV system would have generated if operated at full-rated power for 24 hours a day for one year [121]. The capacity factor has direct implications on the cost of generation [122]. The CUF of the system does not take into account irradiation for the location and degradation of solar panels grid availability. It is an indication of how well the plant is utilized.

CUF= Energy Output (kWh) / (365 X 24 X Installed capacity of the Plant) (4.6)

v. **Performance Ratio (PR):** The performance ratio given by Eqn. 4.7 is the ratio of final yield (Y_F) to reference yield (Y_R) and is a dimensionless quantity. The performance ratio is expressed as a percentage and is a tool for comparison of PV systems installed in different parts of the world. It is also called the 'Quality Factor". PR values are generally reported on a monthly or yearly basis; however, weekly or daily values help in the identification of component failure. The PR indicates the performance of the PV plant at a given irradiation level. Now, if the same plant were to be moved to a different location with different irradiance levels, then the performance ratio factor would consider the irradiation level at that location. PR in contrast to CUF evaluates the plant against the energy available from the sun thus it automatically discounts night times, when the sun does not shine. It is therefore an important parameter for comparing the quality of a plant at different locations. The closer the values of PR of the solar PV plant to 100% more efficient its operation.

$$PR = Y_F/Y_R \quad (4.7)$$

4.3 Performance Analysis of Grid-Connected PV System Based on Data Obtained from SCADA

The performance analysis of an SPV system involves the evaluation of various parameters that are recorded by data acquisition systems. Performance analysis is based on values of incident solar radiation (Global Horizontal Irradiance-GHI), module temperature, ambient temperature, and energy generation. The values are generated throughout the 24-hour duration in the SCADA centre, however, the average of only those values is considered, during which the inverter is ON i.e., when the radiation is more than 5 W/m^2. Daily, monthly, and yearly reading of various parameters is obtained by taking an average of these 15 minutes of data. The average CUF of the SPV system is 13.84% which lies within the range of CUF of wellperforming plants in India. The variation of CUF during the study period is shown in Fig. 4.4.

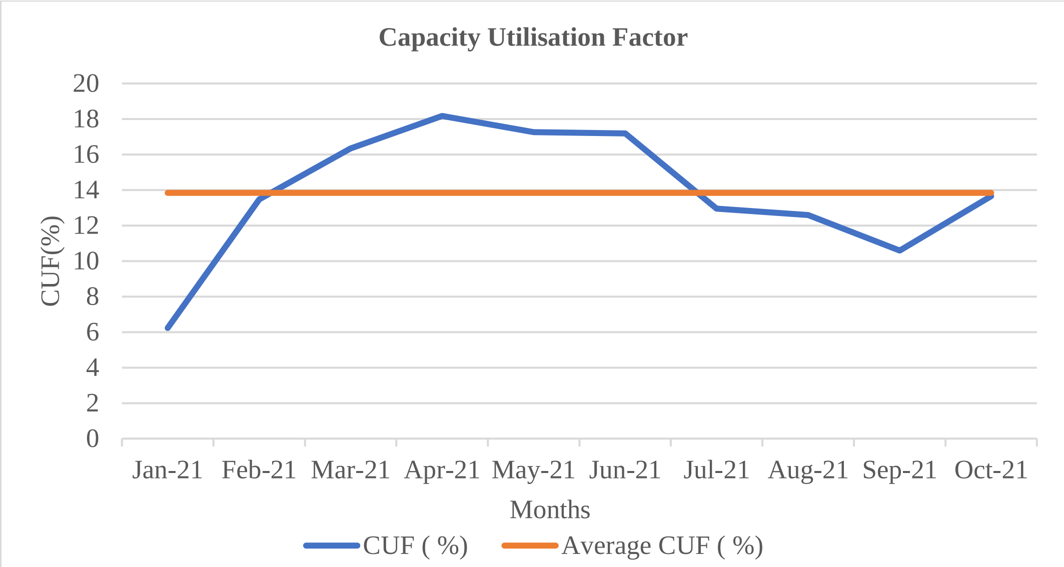

Fig. 4.4 Variation of Capacity Utilisation Factor During the Study Period

The annual average Performance ratio (PR) of the SPV system is around 70% which indicates its satisfactory operation. Fig. 4.5 shows the variation of PR during the study period.

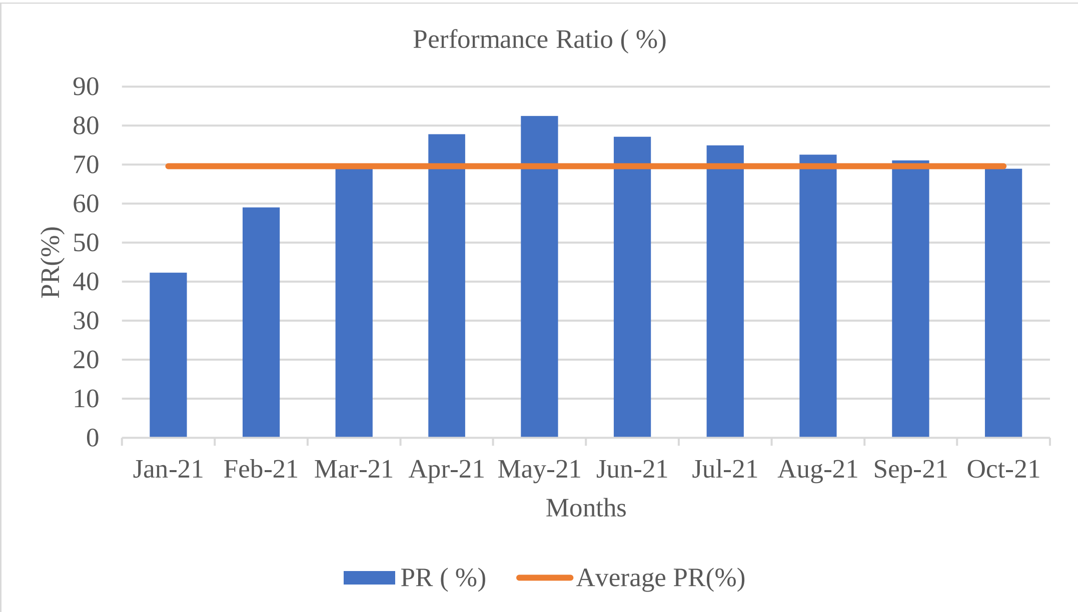

Fig. 4.5 Variation of Measured Monthly Performance Ratio for the Study Period

4.4 Integration of SPV Plant with Battery Energy Storage System

With the advent of economical battery energy storage systems at large-scale levels, it was later proposed to install a battery storage plant as a pilot project for the Delhi Secretariat building. To initiate the pilot project the following two methodologies are analysed and comparative analysis is represented for both Time of Day (ToD) and flat tariff regimes.

Case A: The analysis is made considering that there is no availability of BESS and is considered a reference case.

Case B: It is considered that whenever there is excess solar energy after self-consumption it will be stored in the battery for usage in subsequent load cycles.

Delhi Secretariat is office building and the load profile indicates more energy consumption during working days (i.e., Monday-Friday) than weekends (i.e., Saturday - Sunday) and public holidays. Given the load profile of the identified building, the condition of surplus solar energy (Case B) will happen during weekends and holidays. The summer month offers an excellent opportunity for saving through battery storage.

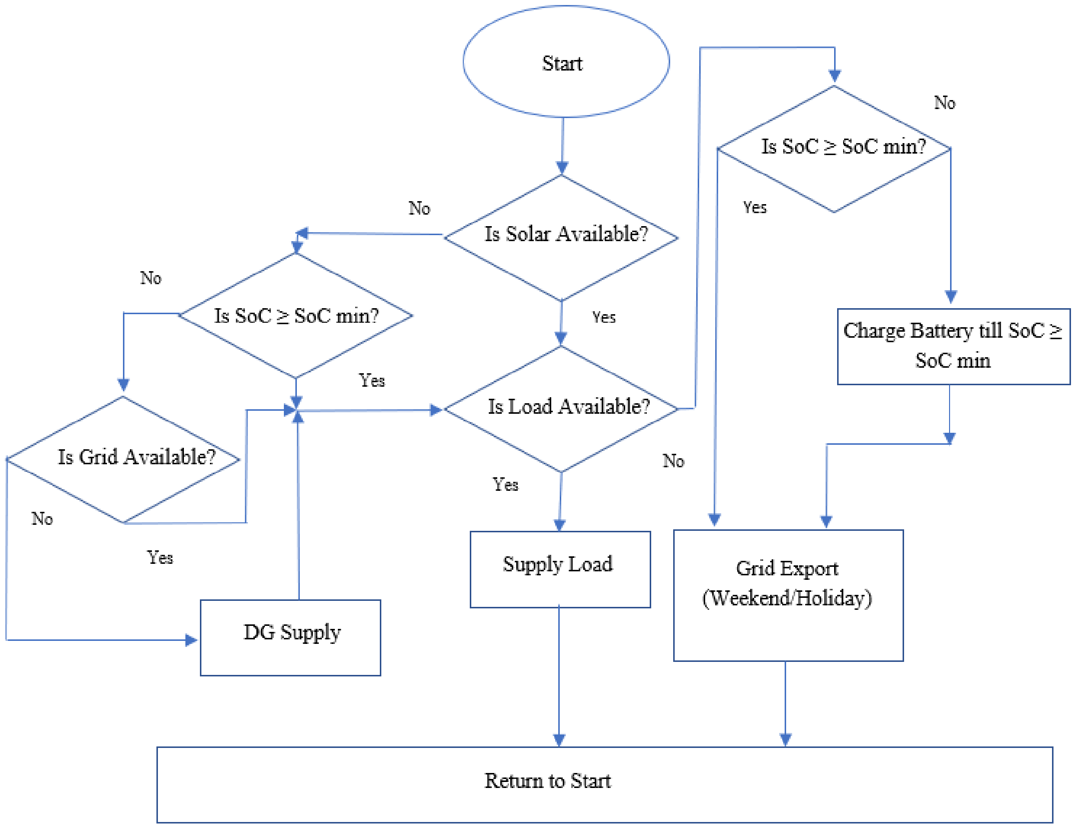

Fig. 4.6 Flow chart of logic used for scheduling the supply of building load

To limit the size and cost of the battery storage, BESS charging from the grid supply has been disabled. The load must be delivered in order of solar, battery, and grid availability. Direct supply of load through solar generation during the daytime has been accorded the highest priority. If the battery's state of charge is higher than the minimum state of charge, battery storage will be used to supply the remaining portion of the load. There may be instances when there is solar generation but the sufficient load is not available (particularly during weekends and holidays). In these cases, excess solar generation will be utilized for battery charging and if the State of Charge (SoC) of the battery is sufficient then solar generation will be exported to the grid through the net metering arrangement. The flow chart of logic used for scheduling the supply of building load is given in Fig. 4.6

The data set of 24 hours for a typical summer day has been incorporated in the General Algebraic Modelling System (GAMS) to obtain optimal battery size. For the identified optimal battery size, the saving in terms of daily energy charges was obtained under flat and ToD tariff regimes.

4.4.1 System Modelling

Even though the Delhi secretariat building's connected load exceeds the plant's present installed capacity of 2 MWp, the system nevertheless delivers excess electricity beyond consumption levels to the utility grid during weekends and holidays using net metering. The tariff structure applicable to the building is tabulated below in Table 4.1.

Table 4.1 Applicable Tariff Structure

Category	Fixed Charges	Energy Charges
Non-Domestic [HT] Supply Type HT (11KV) < 3kVA	₹250 /kVA/Month	₹8.50 /kVAh

Peak load though occurs normally for a small percentage of time usually resorted by generation capacity addition or by load shedding. ToD tariff is a crucial Demand Side Management (DSM) measure that is used to encourage users to shift some of their non-essential loads from peak hours to off-peak hours, leading to the improvement of system load factor through peak demand reduction. It is recognized widely across the energy industries. The ToD tariffs allow resources to be distributed more wisely and effectively by reflecting the true cost of producing, distributing, and supplying energy in price signals sent to customers [123].

As per Delhi Electricity Regulatory Commission (DERC) regulations, all consumers (other than residential) with a sanctioned load or Maximum Demand Indicator (MDI) (whichever is higher) of 10kW or 11kVA and above are subject to the ToD tariff [124]. Table 4.2 provides the pertinent time slots for peak and off-peak hours, together with the percentage rebate and the surcharge rates.

Table 4.2 ToD Tariff Schedule as Per DERC Regulations

Peak Hours (hrs)	**Energy Charges Surcharge (%)**	**Off-Peak Hours (hrs)**	**Energy Charges Rebate (%)**
1400–1700 & 2200 – 0100	20%	0400–1000	20%

Though electricity failure from the grid is very rare in buildings yet 3 DG sets of 750 kVA are installed in the Delhi secretariat to meet the emergency load in case of grid supply failure. In the present study, BESS is proposed for the Delhi secretariat to work in conjunction with the existing solar plant. The operation of the plant for power generation, storage, and supply to load/grid can be controlled to target an overall reduction in energy bills through peak shaving without compromise or major change in usage pattern. A common AC bus bar connects the solar PV panel, the grid, the diesel generator, the battery bank, and the load. The conversion of the solar PV panel DC output to AC output at the AC bus bar is done by Inverter. An inverter/charger unit is installed between the battery and AC bus bar for conversion of AC to DC and DC to AC during the battery charging and discharging cycles respectively. DG sets are connected to a common AC bus bar for meeting the emergency load in case of power supply failure from the grid. Fig. 4.7 shows the basic setup of the system that is employed for the present study.

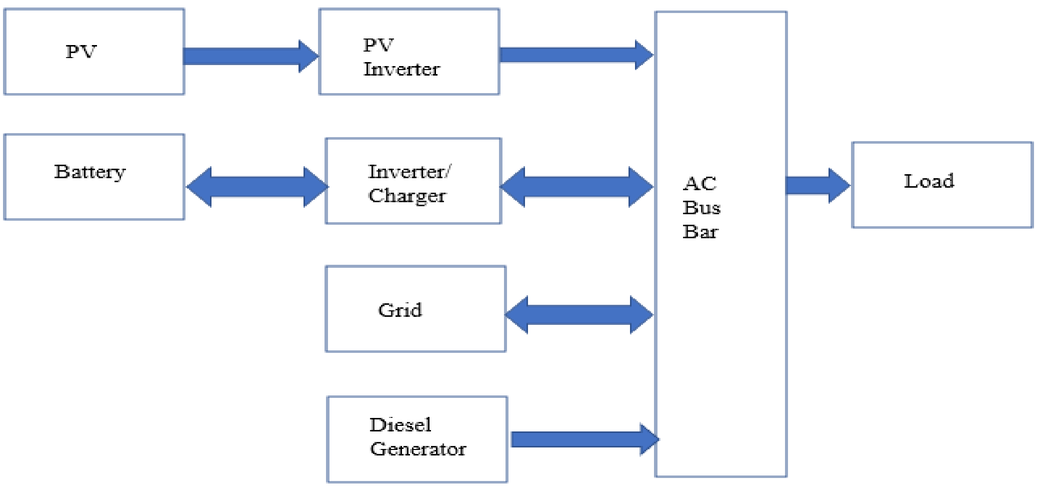

Fig. 4.7 Block Diagram of Basic System Configuration

The Delhi Secretariat building provides an excellent range of battery storage systems for peak load shaving during summer seasons on account of the considerable variation of average weekday and weekend loads.

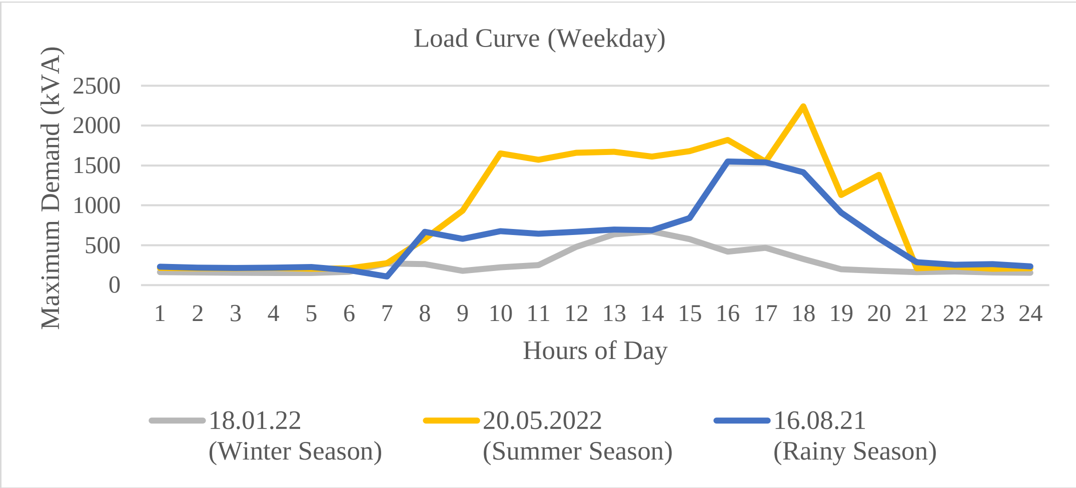

Fig. 4.8 Daily Load Curve Profile (Weekday)

The present study has analysed the energy bills from August 2021 to August 2022. The major load in the building is due to chillers, AHU, pumps, lifts, and room air conditioning units. Fig. 4.8 & 4.9 display the load profiles of the building during weekdays and weekends on typical days of the winter season (January), summer season (May), and the rainy season (August). The high peak demand observed during summer and rainy weekdays is a result of the high use of the air conditioning systems in the building. It can be observed from Fig. 4.8 that during weekdays maximum demand reaches as high as 2250 kVA while during the weekend it varies between 50 and 750 kVA as shown in Fig. 4.9.

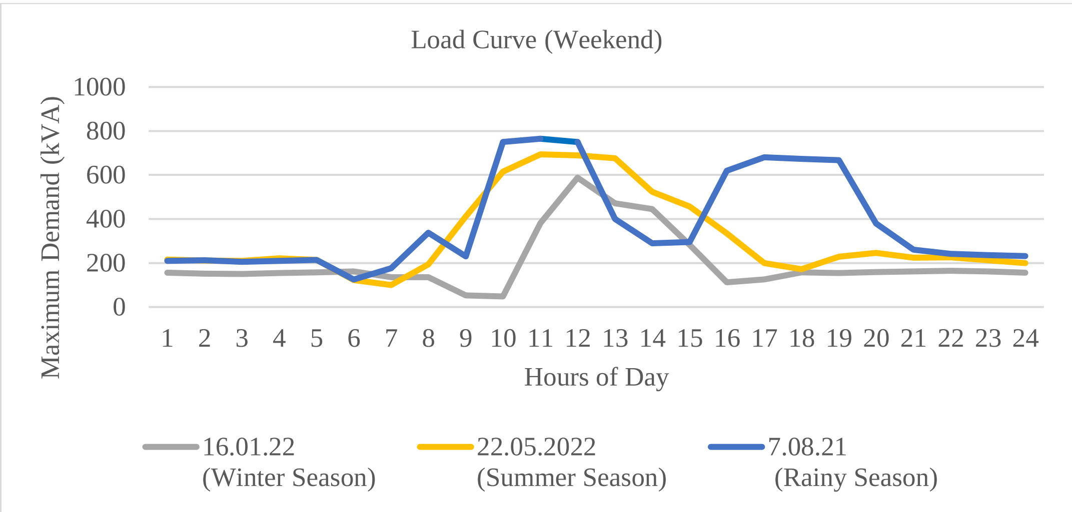

Fig. 4.9 Daily Load Curve Profile (Weekend)

It can be observed that on weekdays from 21:00 hrs - 6:00hrs the load is almost constant and is generally less than 250 kVA and the load in the building starts increasing from 7:00 hrs to meet water pumping and cooling requirements in office rooms.

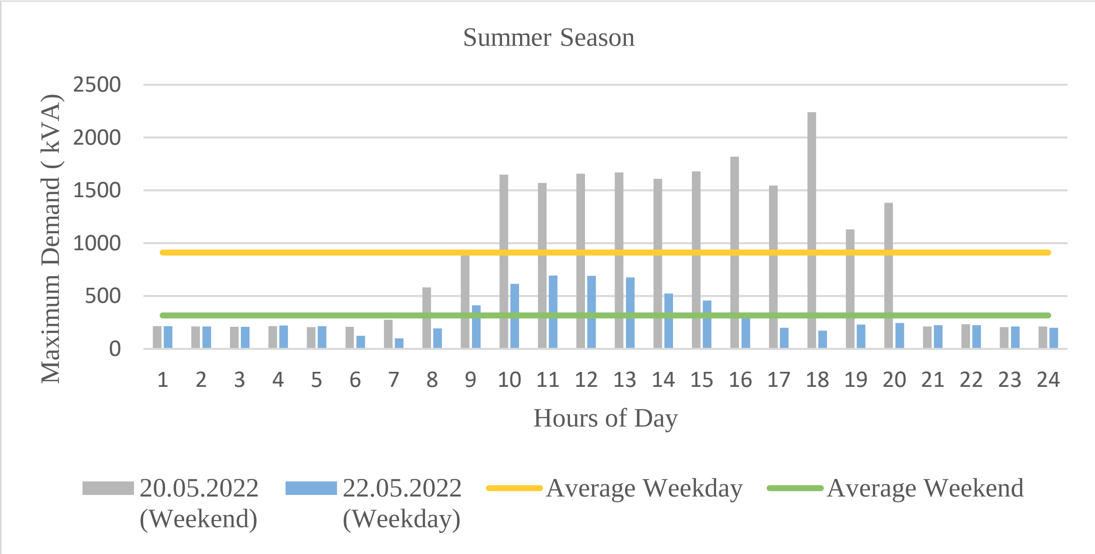

Fig. 4.10 Difference Between Weekday and Weekend Load for a Typical Summer Day

Further examination of the daily load curve data of the building for a typical day yield that the difference between weekday and weekend load for a typical summer day is 600 kVA which is represented in Fig. 4.10 mainly on account of air conditioning requirements during weekdays. The corresponding values for winter and rainy seasons are 80 and 190 kVA respectively.

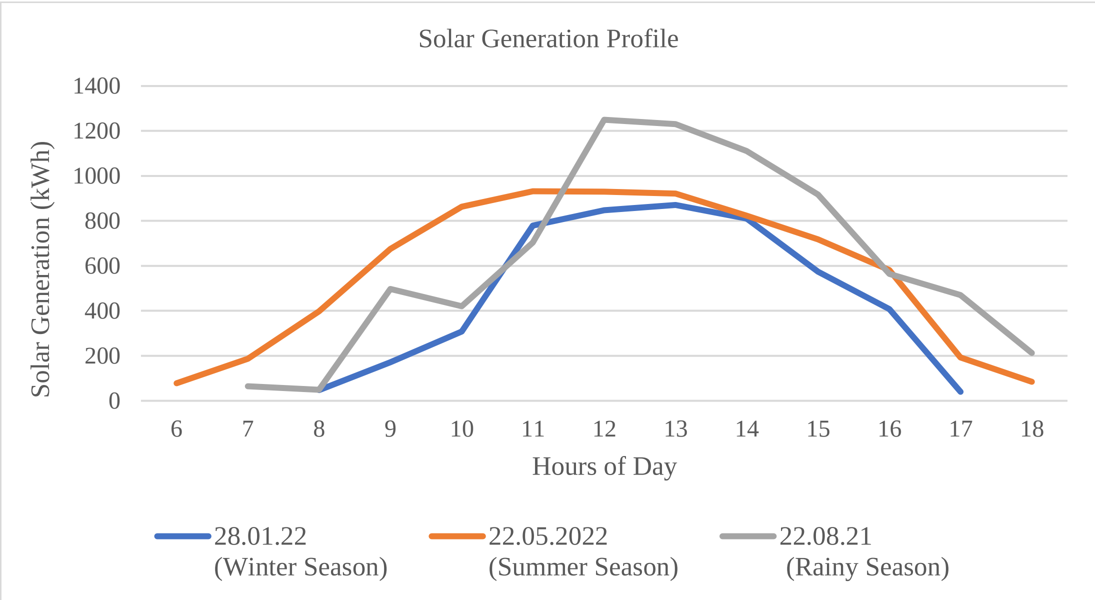

Fig. 4.11 Solar PV Generation Profiles During Different Seasons

Fig. 4.11. displays the solar PV generation profiles of the building during typical days of the winter season (January), summer season (May), and the rainy season (August) taking into account the installed capacity of 2 MW. It can be observed that solar generation is comparatively more in the rainy season during the study period.

The high solar PV generation during rainy seasons can be attributed to the absence of pollutants and the natural cleaning of solar panels due to rain.

The proper sizing of BESS for peak load shaving is a major challenge that depends on the load usage patterns and the variation of solar generations. The analysis of the variation of load and solar generation profile performed in this section will be utilised to simulate the optimal size of the battery in the next section.

4.4.2 BESS Sizing

The size of the battery is optimized subject to the objective function of minimizing energy charges, ensuring continuous supply while adhering to system constraints. The energy charges are given by Eqn. 4.8.

$$\text{Energy Charge} = \sum_{t=1}^{24} E_{Grid} \times T_{Grid} + \sum_{t=1}^{24} E_{pv} \times T_{pv} + \sum_{t=1}^{24} E_{Bat} \times T_{Bat} + \sum_{t=1}^{24} E_{DG} \times T_{DG} + \sum_{t=1}^{24} Loss_{Bat} \times T_{Bat} \tag{4.8}$$

Where E_{Grid} is energy exchanged with grid in kWh, T_{Grid} is grid tariff in INR/kWh, Epv is energy received from solar PV plant in kWh, Tpv is solar energy tariff in INR/kWh, E_{Bat} is energy exchanged with BESS in kWh, T_{Bat} is BESS tariff in INR/kWh, E_{DG} is energy received from DG in kWh, T_{DG} is DG tariff in INR/kWh, $Loss_{Bat}$ is battery loss in kWh.

The objective function solution is determined using the following constraints. The battery state of charge at a given time t is given by Eqn. 4.9.

$$SOC(t) = SOC(0) + SOC(t-1) + (P_{Bat-c} \times \eta_c) - (P_{Bat-d} \times \eta_d) \tag{4.9}$$

Where SOC is the state of charge at t and t-1, P_{Bat-c} is battery power during charging in kW and P_{Bat-d} is battery power during discharging and η_c and η_d efficiency during charging and discharging respectively.

The power balance equation can be represented as given in Eqn. 4.10.

$$P_G + P_{pv} + P_{Bat-d} + P_{DG} \geq P_{load} + P_{Bat-c} \tag{4.10}$$

Where P_G, P_{PV}, P_{DG} and P_{load} are grid power, solar PV power, DG power and load power in kW respectively.

The $Loss_{Bat(t)}$ is the cumulative hourly loss in battery capacity that can be calculated as given in Eqn. 4.11 [125].

$$Loss_{Bat}(t) = Loss_{Bat}(t-1) + (P_{Bat-d}(t) + P_{Bat-c}(t)) \times z \tag{4.11}$$

where $Loss_{Bat}$ is battery loss at t and t-1 and z is ageing coefficient taken as 5×10^{-4}.

Fig. 4.12 shows the effect of BESS capacity on the daily energy charges using GAMS. In order to obtain optimal battery size, the algorithm starts with an initial battery size of 100 kWh with a step size increase of 50 kWh. It is observed that increasing the battery capacity will lead to a reduction in energy costs. The curve will reach a minimum value and after that will start increasing signifies that any further increase in the capacity will increase the energy costs. From the given daily dataset, the optimal values selected for battery storage capacity come out to be 1250 kWh.

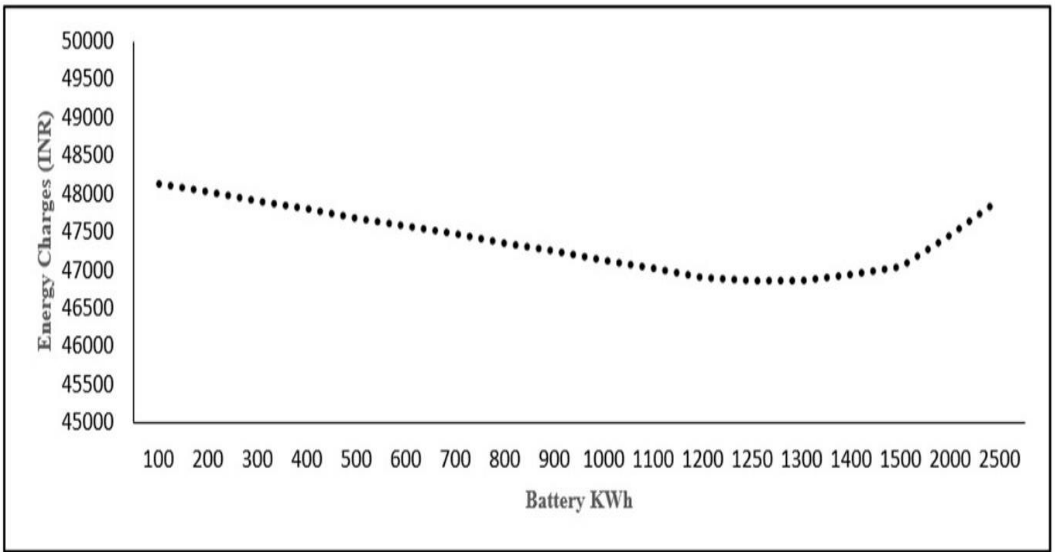

Fig. 4.12 Annual Energy Charges as a Function of the BESS Capacity

4.5 Simulation Results and Discussion

In the present study, two cases were simulated:

Case A: This case is taken as a reference case and has no provisions for battery storage for storing excess generated energy. In the present case, the excess energy during weekends and holidays is supplied to the grid through a net metering arrangement. The surplus energy exported to the grid is tariffed at average power purchase charges (APPC) as fixed by the regulator. The APPC charges for 2021-22 are Rs. 3.85/kWh. In this reference case, the daily energy cost is calculated with and without the ToD tariff regime.

Case B: In this case, it is assumed that excess solar energy generation beyond consumption levels in the building is stored in the battery. The stored energy in the battery will be utilised to supply load in subsequent cycles depending on the state of charge. The present case forbids charging of battery through the grid during off-peak hours.
The simulation is carried out under the following assumptions:

i. Daily energy cost is calculated on the basis of a data set of typical summer days during 2022 that offers the maximum opportunity for storage. The analysis can be further extended to monthly savings and annual savings by incorporating monthly and yearly datasets.

ii. The battery charging and discharging efficiency are taken as 95% and 90% respectively.

iii. Solar PV unit charges and battery energy charges are taken as ₹4.50/kWh and ₹4.80/kWh.

iv. DG tariff is taken as ₹15.00/kWh and grid tariff during normal hours is taken as 12.00/kWh.

Table 4.3 Comparisons of Simulation Results

Daily Energy Cost (INR)	**Without BESS (Case A)**	**With BESS (Case B)**
	Rs. 48243 (With ToD)	Rs. 46852(With ToD)
	Rs. 47339 (Without ToD)	Rs. 46618 (Without ToD)

For an optimum battery size of 1250 kWh. The results of simulation using GAMS linear programming are presented in Table 4.3 and Fig. 4.13. The results demonstrate that the ToD regime offers more saving opportunities in comparison to the flat tariff rate regime.

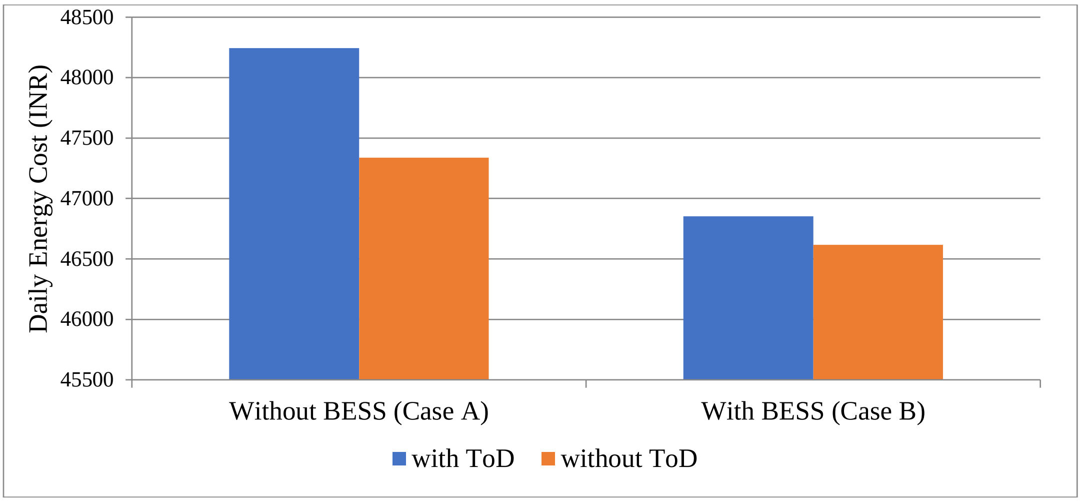

Fig. 4.13 Annual Energy Charges as a Function of the BESS Capacity

There is a daily saving of in tune of ₹1500/- under the ToD regime which amounts to a saving of ₹5 Lakh per annum. Despite high payback time, the government of Delhi may consider installing the BESS on a pilot basis as a demonstration project. The payback time will be bound to come down with the falling price of BESS.

4.6 Analysis and Discussion

Battery energy storage systems by storing energy when the demand is low and discharging it in peak periods enables users to save on electricity tariffs and also helps utilities in peak load management. Peak load management is a sensitive factor from the planning and operation point of electrical grids. Peak demand affects network planning since the electrical infrastructure of Transmission and Distribution (T&D)

systems must be designed to cater for maximum system demand. However, most of the time the T&D infrastructure remains underutilized. Instead of investing in the upgradation of T & D infrastructure, utilities either resort to load shedding or to dynamic pricing practices.

With growing RE penetration, the current energy system is going through a phase of transition wherein traditional, centralized, and larger power plants are being replaced with smaller, distributed power plants. As renewable energy generation experiences intermittent fluctuations, the use of BESS in coordination with solar PV can store excess energy during peak production and release it when demand is high or when renewables are producing less. The results of the present study demonstrate that the deployment of battery energy storage systems in coordination with distributed energy sources like PV will result in making the overall energy system more reliable, efficient, and economical without affecting usage patterns.

Presently high cost of batteries is the major impediment and in order to make battery storage affordable, the Government has approved a VGF Scheme for setting up 4,000 MWh of BESS. The scheme has provision for VGF to the extent of up to 40% of capital cost for BESS, which will bring down the cost of electricity from BESS.

Much like the support extended to solar PV plants in the past, BESS now stand in need of similar financial backing to attain parity and ensure its effective integration. Just as financial incentives propelled the growth of solar PV technology, providing BESS with comparable support can accelerate its adoption, optimization, and grid stability benefits. By equipping BESS with the necessary financial resources, India can harness the full potential of this technology, enhance grid reliability, and usher in an era of cleaner, more sustainable energy.

4.7 Concluding Remarks

The present study has conducted a techno-economic analysis for a grid-connected solar PV-BESS system with the objective of determining energy costs. From the analysis, it is observed that the ToD regime offers more saving opportunities in comparison to the flat tariff rate regime. Further, it is demonstrated that the sizing of the battery is a function of the ToD tariff and input cost of power. The results present a saving scenario in which there is a daily saving of around ₹1500/- under the ToD regime which amounts to a saving of ₹5 Lakh per annum. In the present scenario though the payback period is large but with the government’s thrust on battery storage and production link incentive schemes for batteries, the payback period is bound to become more attractive in the near future.

CHAPTER 5

ASSESSMENT OF DUST SOILING IMPACT AND DETERMINATION OF CLEANING FREQUENCY FOR PERFORMANCE IMPROVEMENT

5.1 Introduction

With one in nine deaths worldwide being related to poor air quality, air pollution is one of the biggest environmental threats to human health. Over 90% of individuals are subjected to air pollution, that is having PM 2.5 concentration > 5 μg/m^3. This leads to almost 6 million premature deaths annually or nearly twice as many as the number of deaths from COVID-19 in 2020 [126]. Apart from this PM in the air affects the energy output of photovoltaic installations. Fine PMs are predominantly anthropogenic, and the primary sources of these particles are incomplete combustion, vehicular emission, dust, and cooking [127]. Renewables 2022 global status report [128] estimated that solar PV will account for approximately 66% of the USD 11.3 billion new investments being made globally in renewable power. In light of significant investments being made in the solar sector globally and in India, it is crucial to understand the performance of PV modules in the Indian climatic conditions. Relating weather conditions with dust accumulation on PV modules will enable us to come up with better predictive models for the power output of PVs in the sense that these models will include the power losses caused by dust accumulation. The importance of optimizing the cleaning cost lies in the fact that cleaning is both time-consuming and costly. "Soiling", on the PV modules is generally not considered and is usually put arbitrarily (~3%) during the design, installation, and operation stage of the PV system [129]. Dust naturally blocks sunlight from reaching the photovoltaic cells, which can drastically reduce the module's power output, and thus accounting for soiling loss and rate of dust deposition needs to be determined fairly accurately.

The Soiling Loss (SL) is determined as per the Eqn. 5.1 given below:

$$SL\ (\%) = \left(1 - \frac{X\ soiled}{X\ cleaned}\right) * 100 \qquad (5.1)$$

where X is the short circuit current or maximum power or daily energy (kWh).

In present study, daily energy generation (kWh) is used to calculate soiling loss. The soiling phenomenon although seems to be simple to calculate mathematically, in practical is a complex problem affected by climatic, localized pollution, mounting configuration, etc. Soiling losses enhance uncertainty and result in a rise in LCOE due to loss of energy production, increased O&M costs, and higher finance rates. Such an investigation will facilitate feasibility studies for suitable cleaning mechanisms and appropriate cleaning schedules.

Unlike previous studies, the present study also attempts to determine the optimal frequency of solar panel cleaning. These findings will be useful to those involved in the study, experiment, design & development and installation of solar photovoltaic systems, particularly in similar polluted regions.

5.2 Dust Accumulation Phenomenon

Particulate matter is a generic term to classify air pollutants comprising suspended particles in the air, varying in composition and size, resulting from various anthropogenic activities. Particles found in the atmosphere, in general, are less than 500 micrometres in diameter which is about 10 times roughly the diameter of human hair. Particulates are categorized using a variety of names based on their size and phase (liquid or solid). Aerosol is the most general name for any small particles, either liquid or solid, that are scattered throughout the atmosphere. If a solid particle is the result of crushing or grinding, it is dust. One term for liquid particles is mist, or more colloquially, fog. Particles resulting from incomplete combustion that are largely carbon-based are referred to as smoke or soot. Particulate matter less than 10 micrometres (PM10) or less than 2.5 micrometres (PM2.5) in diameter is the most commonly measured parameter to estimate the airborne dust concentration. In the present study, we will limit our scope to dust and particulate matter which will be used interchangeably throughout the study. Dust can originate from man-made, natural, or a combination of sources. Burning of fossil fuels and volcanic eruptions results in the release of primary particles. When the primary pollutants interact with one another or other elements of the atmosphere, secondary dust particles are created. The transportation of the particles occurs in several modes like creep, saltation long and short-term suspension depending on wind speed and particle size. The dust transportation phenomenon is shown in Fig. 5.1.

The adhesion of these dust particles to the PV surface will depend on the various properties of the PV surface and dust particles like degree of smoothness or roughness, electrical properties (conductivity and charge), temperature, degree of dryness, presence of dew etc [130]. The rate at which dust particles accumulate on the PV surface can be given by Eqn. 5.2.

$$\text{Accumulation} = \text{Deposition} - \text{Rebound} - \text{Resuspension} \tag{5.2}$$

Deposition implies particles from the atmosphere impacting the surface, rebound implies bouncing back immediately from the surface without adhering and resuspension refers to the removal of deposited material from the surface. Rain though considered a natural cleaner, but rain can enhance the soiling if it occurs for a short duration and at low intensity. In such conditions, the rain droplets coalesce suspended PM and aid deposition on the surface of the PV modules.

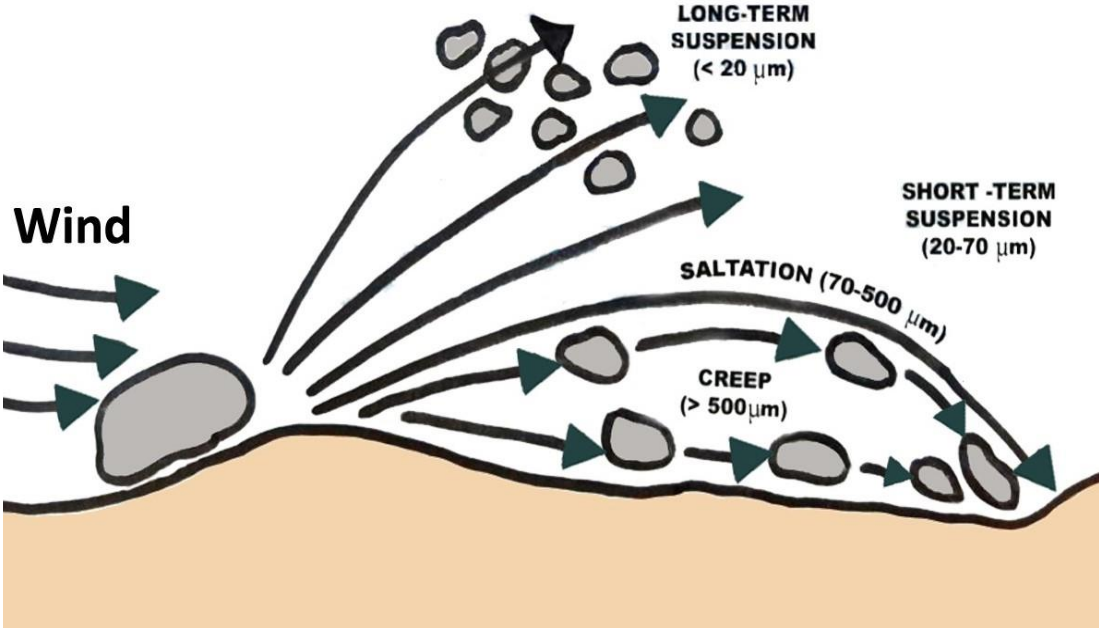

Fig. 5.1 Dust Transportation Phenomenon

The presence of numerous factors that affect soiling processes can be classified into first installation-based factors like height of solar PV installation, tilt angle, orientation, characteristics, and PV technology characteristics and second, various environmental factors that comprise wind velocity, dust characteristics, ambient temperature, rainfall intensity, and humidity etc. The effect of some major factors influencing the soiling are presented below:

i. **Tilt Angle:** The tilt can be fixed or variable tilt utilising a solar tracking system. The impact of tracking on the soiling has been evaluated in several research works reported in the literature [131] [132] [133] [134]. The outcome of these studies has demonstrated that fixed-tilt solar photovoltaic systems have more soiling loss.

ii. **Airborne Dust Particle Matter (PM):** The efficiency of solar energy panels is significantly impacted by particulate matter [135] and it has been observed that increased PM concentrations cause more dust accumulation [54] [136]. With an adjusted coefficient of determination of 70%, it has been demonstrated that among various environmental factors, the PM had the strongest link with soiling [137].

iii. **Orientation:** The accumulation of dust will be more on panels if the orientation is in the direction of the wind as compared to when they are in the opposite direction [53] [59] [138].

iv. **PV Technology Effect:** Depending on the technology being utilized, soiling can have a different effect and it has been observed that the monocrystalline panel's efficiency decreased by a higher proportion than the polycrystalline panels due to soiling [139] [140] [141].

v. **Height of Installation:** The height of the PV installation contributes to the amount of soiling on its surface. The results [142] [143] obtained have shown that PM10 dust concentration decreased with height and followed an exponential profile. The PM2.5 particles are found to be highest below 5 meters from the ground level primarily due to vehicular traffic [144].

vi. **Rainfall:** Precipitation has been shown to play a dual role in terms of dust accumulation. The effect of rainfall has been studied and discussed in several research works [145] [146]. Rainfall can be a good cleaning agent based on its high frequency and large intensity [147]. Light rainfall generally increases the coagulation of dust on the surface panel and thereby increases the effect of soiling [148].

vii. **Wind Speed:** According to the [149] experiment, a wind speed < 2km/hr is beneficial as it causes less dust deposition, while wind speeds > 6 cause more dust accumulation in high ambient dust concentrations.

viii. **Occurrence of Dew:** Dew accelerates the cementation process and increases the difficulty of removing the dust. If controlled or improved, dew can also be beneficial as it can help clean the PV modules. A comprehensive literature survey to assess the impact of dew on the output of solar PV modules was carried out in the study [150] and it was demonstrated that 61% of researchers studying the dew-soiling nexus have suggested that enhancement of dew water formation ensures self-cleaning of solar panels and thereby enhances their performance, while 39% of research have recommended dew suppression.

ix. **Season Effect:** The rate of soiling is not uniform throughout the year because of the seasonal variations. The present research shows that the impact of dust on PV module performance was greater in winter months as compared to summer and rainy seasons.

5.3 Experimental Set-Up and Data Collection Methodology

Delhi has the distinction of being one of the most polluted mega-cities in the world [151]. Considering pollution levels in Delhi, the present study is undertaken at Delhi Technological University (DTU) main campus at Shahabad Daulatpur, Delhi. A grid-connected solar plant of capacity 440 kWp is operational at DTU campus since 2018. However, the present study demands separate monitoring of energy data for a certain set of panels as per their cleaning schedule therefore, a separate plant of capacity 1.34 kWp was installed at the roof of the Electrical Engineering block of DTU for experimental study purposes. The plant has four panel c-Si of 335 Wp capacity and a cleaning schedule of 7 days, 15 days and 21 days was followed separately for three solar panels while the fourth panel was left uncleaned. The specification of the solar panel used in the experiment is given in Table 5.1. It is a well-known fact that environmental factors such as temperature, wind velocity, dust, rainfall, ambient pollution levels etc. affect solar yield. Out of the various factors that affect soiling, deposition of dust on solar panels depends mainly on ambient pollution levels thus linking deposition levels with ambient conditions will help in determining cleaning schedules that will prevent loss of generation. Usually, the quantity of energy lost by the PV module is used to determine the impact of soiling.

Fig. 5.2 The Physical Arrangement of Solar Panels at DTU

Table 5.1 Specifications of PV Panels Used in the Experiment

Model ENVIRO-PVM6-335	
Make: Havells	
Type:	Multicrystalline Module
Rated power	335Wp
V_{mp}	37.9V
I_{mp}	8.85A
V_{oc}	46.27V
I_{sc}	9.41 A
Max system voltage	1500V

In the DTU campus, the main source of dust is due to its vicinity to the Bawana industrial area and ongoing constructions in and around the location. DTU is one of the 14 sites that are emerging as new hotspots having registered a higher seasonal average than the mean of recognized hotspots i.e., 197 micrograms per cubic meter [152].

The setup as shown in Fig. 5.2 is located on a rooftop at Electrical Engineering block approximately 22 meters above the ground at a tilt angle of 19 degrees (same as the latitude angle). During the test duration, considerable care was taken to avoid any dust removal from the uncleaned panel through any unwanted means except for natural causes like wind or rain. Hoymiles MI-1500 series microinverter, with a maximum output power of 1500 W is used. It can connect up to 4 panels at once and allows monitoring of each module. The collected data can be uploaded to the monitoring platform S-Miles cloud via Hoymiles data transfer units using 2.4G wireless communication. The required climate and weather information was extracted by the TrackSo weather system installed at the test location. The block diagram of the experimental setup is shown in Fig. 5.3.

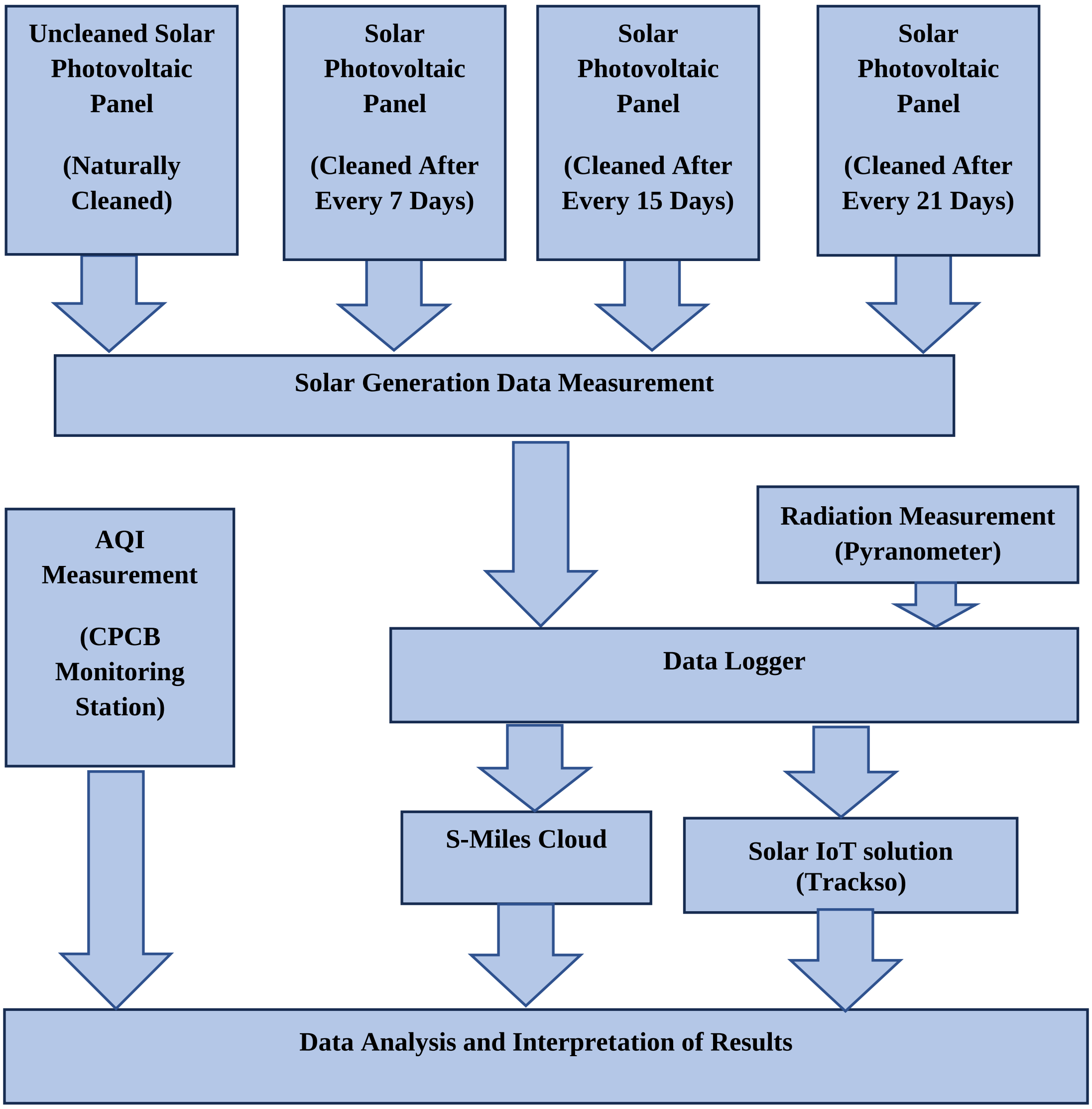

Fig. 5.3 Procedure to Evaluate the Impact of Accumulated Dust on PV Performance

The generation output of the pyranometer and PV panel is connected to the data logger. The data acquisition system will retrieve the information and update data at periodic intervals. The data so collected is fetched through an IoT-based cloud system for analysis. The Air quality data including the concentration of PM 2.5 and PM 10 of the site are obtained from the CPCB air quality monitoring station located at the DTU campus [153].

5.4 Data Analysis

The data obtained regularly has been analysed to establish the relationship between dust concentration and insolation in Delhi. The National Air Quality Monitoring Program (NAMP) is a nationwide initiative to measure ambient air quality and is being carried out by the Central Pollution Control Board (CPCB). Air Quality Index (AQI) is an index number that transforms various pollutants into a single number. It conveys information about various pollutants to the general public in a manner that is easy to understand. AQI is divided into six categories, each category denotes a different amount of pollution and affects people's health differently. As per CPCB, there are six AQI categories, namely good, satisfactory, moderately polluted, poor, very poor, and severe and each one is represented by a different colour code [153]. Each of these categories is decided based on ambient concentration values of air pollutants and their likely health impacts. The AQI of location is determined by eight main pollutants: fine particles (PM2.5), inhalable particulate matter (PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO), ozone (O_3), and carbon monoxide (CO), ammonia (NH_3), and lead (Pb). All the eight pollutants are monitored. The calculation of the overall AQI is contingent upon the availability of data for a minimum of three pollutants, one of which must necessarily be PM2.5 or PM10. There are 38 Continuous Ambient Air Quality Monitoring (CAAQM) stations in Delhi and one of the CAAQM stations is located at DTU [154]. Since the AQI data is being taken from the same site, the chances of uncertainty in the correlation between AQI and insolation are therefore minimized. To classify AQI levels, colour coding as prescribed by CPCB is taken in the present study. The methodology for relating AQI with insolation data involves sorting daily data in bins corresponding to levels of the AQI category. The curve is plotted, by averaging the insolation data for a particular category.

5.4.1 Analysis of the Influence of Air Pollution on Solar Insolation

In addition to other variables, the level of air pollution has a significant impact on the amount of solar radiation that reaches the ground. Fig. 5.4 illustrates the relation between AQI and radiation reduction. The relation between irradiance and AQI was fitted by the second-order polynomial. The value of the fitting coefficient R^2 is 0.938. The fitting correlation coefficient is very high and close to 1. Thus, it can be concluded that better air quality will result in better solar energy utilisation.

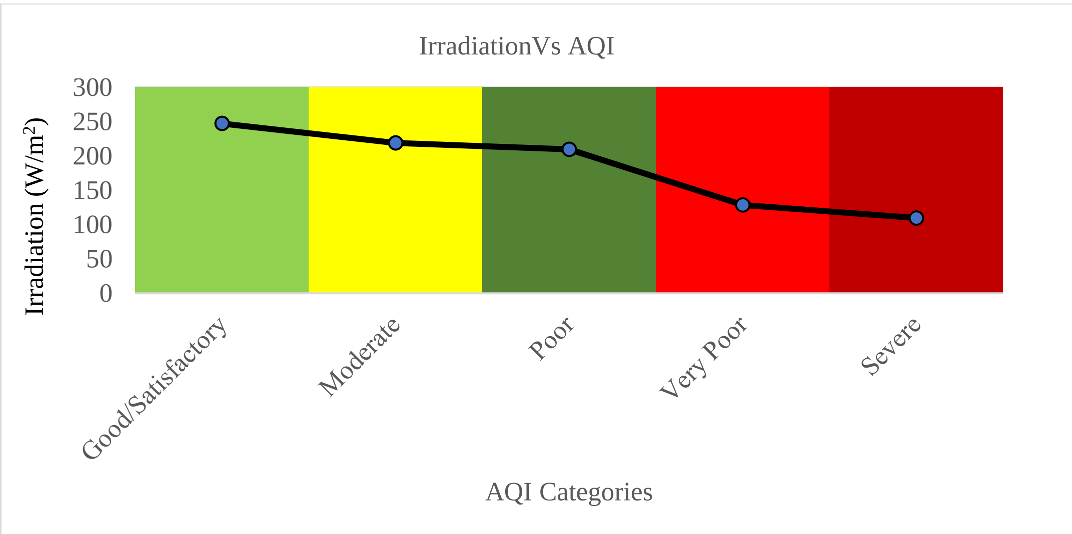

Fig. 5.4 Relation Between AQI and Insolation Reduction

The curve is obtained for all pollution conditions that have been observed during the study period. From above, the equation relating Irradiance and AQI can be written as given in Eqn. 5.3:

$$Irradiance = -0.0003x(AQI)^2 - 0.2416(AQI) + 267.41 \quad (5.3)$$

During the study period, it has been observed from data that a major natural contributor to clean air in Delhi is the occurrence of rainfall. There were no rainy days in severe & very poor category days and only one rainy day in the poor day air category during the study period. But there were 30 and 39 rainy days during moderate and satisfactory category days respectively. The prominent pollutant identified from data during the study period is PM 2.5. Apart from PM 2.5, PM 10 is another major pollutant during the study period.

5.4.2 Dust Characterization

Scanning Electron Microscope (SEM) is used to observe the morphology of dust. Dust samples were collected on the glass substrate of dimensions 1cm X 1cm that was placed at the same tilt angle near the experimental solar panels set up. The results of ZEISS EVO Series SEM EVO 50 and EVO 18 were analysed using Image J software and it has been observed that the particles' size of less than 2.5 micrometres are predominant and are sufficient to reflect and scatter incoming solar radiation, thereby lowering the quantity of radiation transmitted through the glass surface. Fig. 5.5 indicates that the dust particles have various and irregular shapes but are mostly spherical.

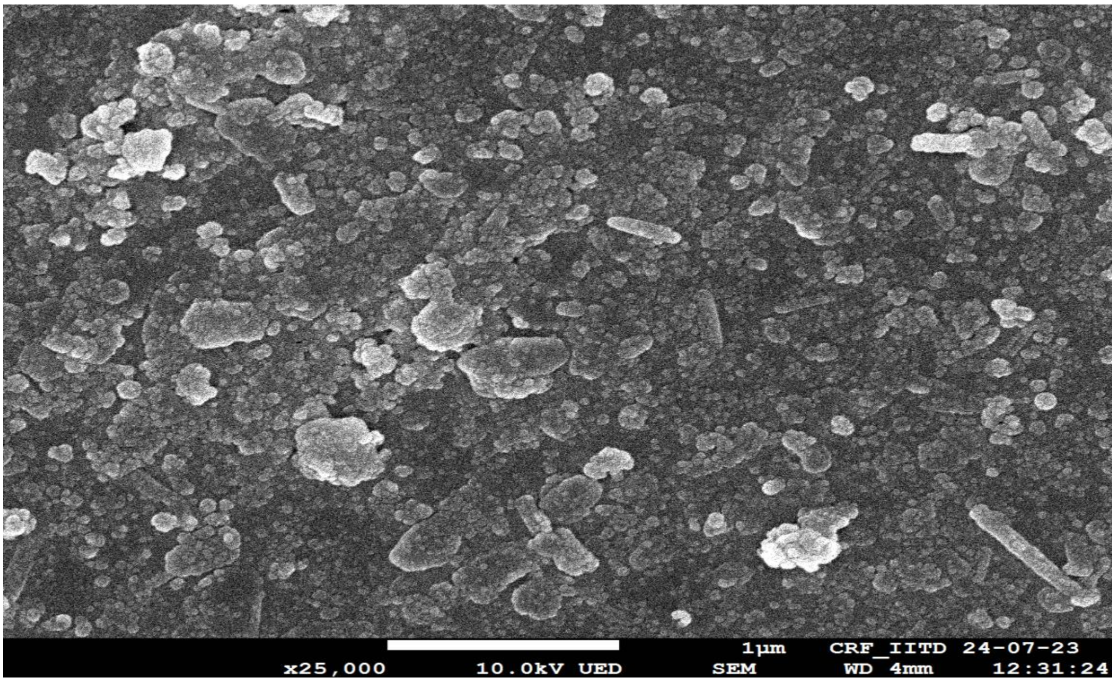

Fig. 5.5 Results of SEM Imaging

Due to the large contact area, the spherical particles offer more adhesion to the glass surface. The analysis further demonstrates that the dust samples are fine and coarse. This further substantiates the finding of an analysis of data obtained from CPCB for DTU location that shows the prominent pollutant identified from data during the study period is PM 2.5.

5.4.3 Particle's Chemical Composition

The dust particles collected on the glass substrate of dimensions 1cm X 1cm also undergo chemical elemental analysis using ZSX primus Rigaku Ultima (WDXRF) X-ray Fluorescence (XRF) spectrometer. The XRF results are shown in Fig. 5.6. It can be observed that oxygen has the highest chemical concentration followed by silicon, sodium, calcium, magnesium, and carbon.

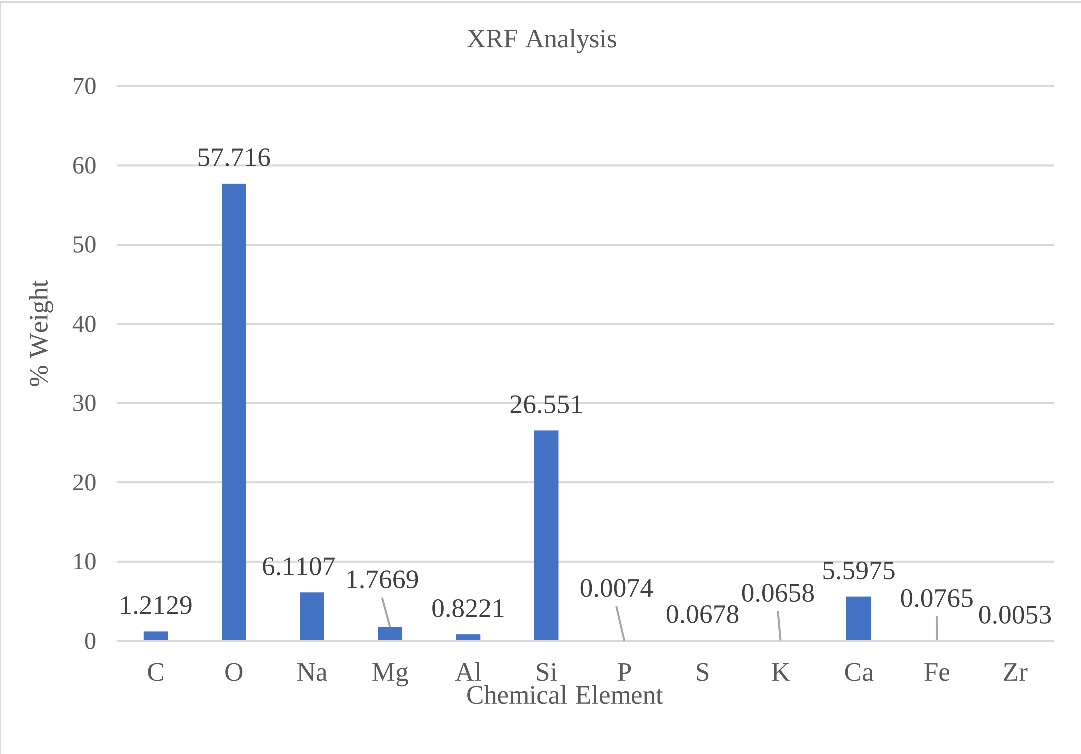

Fig. 5.6 Particles Chemical Elemental Analysis Using XRF

The rest of the composition includes aluminium, iron, sulphur, potassium, phosphorus, and zirconium.

5.4.4 Effect of Cleaning on Solar Generation

The complete experiment test duration can be divided into November to January (Winter months), February to April (Spring and onset of summer season months), and May to August (summer and onset of rainfall season months). There was no rainfall in the period from November 2022 till January 31, 2023, so this period can also be termed a rain-free period from data comparison and analysis point of view. For the sake of simplicity initially, we have considered data from only two panels i.e., the energy output of uncleaned and 7-day cleaned panels. The solar panel is cleaned periodically every 7th day and the effect of cleaning the panel is visible from the difference in energy generation in uncleaned and periodically 7 days cleaned panels depicted by Δ E during rain-free period as shown in Fig. 5.7. It is observed that after cleaning on the 7th day the difference between the energy generated by uncleaned and 7 days cleaned panels is increasing. The difference is higher in initial duration, and it slows down as the dust surface density increases.

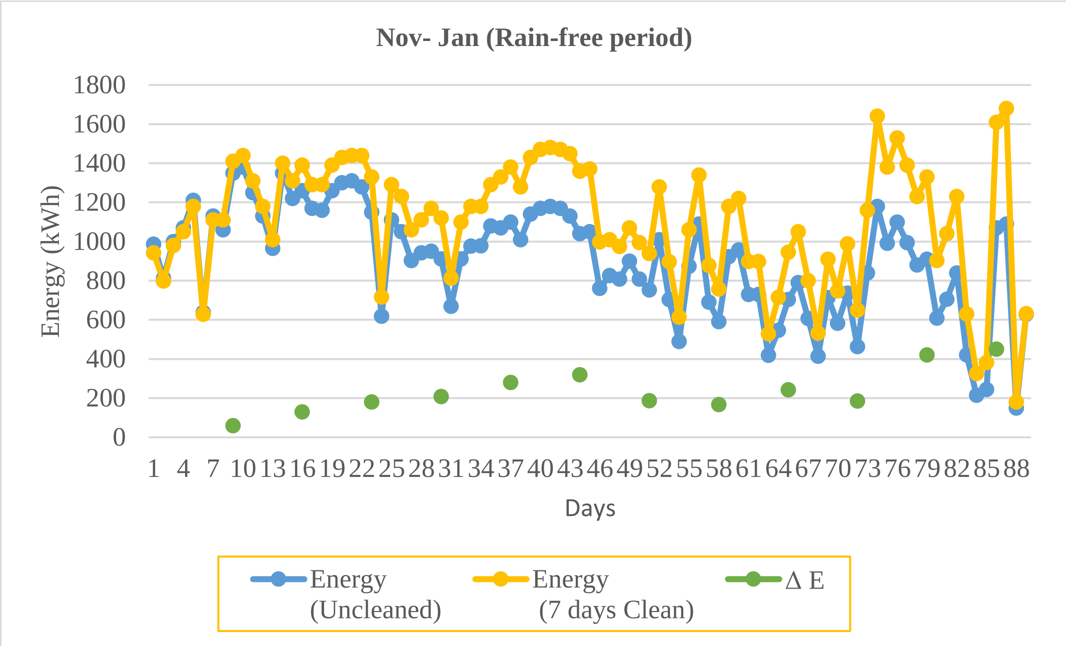

Fig. 5.7 Analysis of November 2022 to January 2023 Duration (Rain-Free Period)

The period from February to April marks spring and the onset of the summer season in Delhi. There were no rainy days in February 2023, (except for one rainy day on 31 January 2023).

Due to rain on the last day of January 2023, the effect of cleaning is not so noticeable during 1st week of February but the effect becomes appreciable during the latter half of February as shown in Fig. 5.8. There were 7 rainy days recorded during March 2023 against a rainy-day average of 1.7 days as per records between 1991-2020. The effect of appreciable rain spells in March particularly during the second half has resulted in a drop of Δ E. Similarly, there were 4 rainy days recorded during April against the past average of 1.0 rainy days. As compared to Fig. 5.7 the curve of Δ E is flatter due to more rain spells.

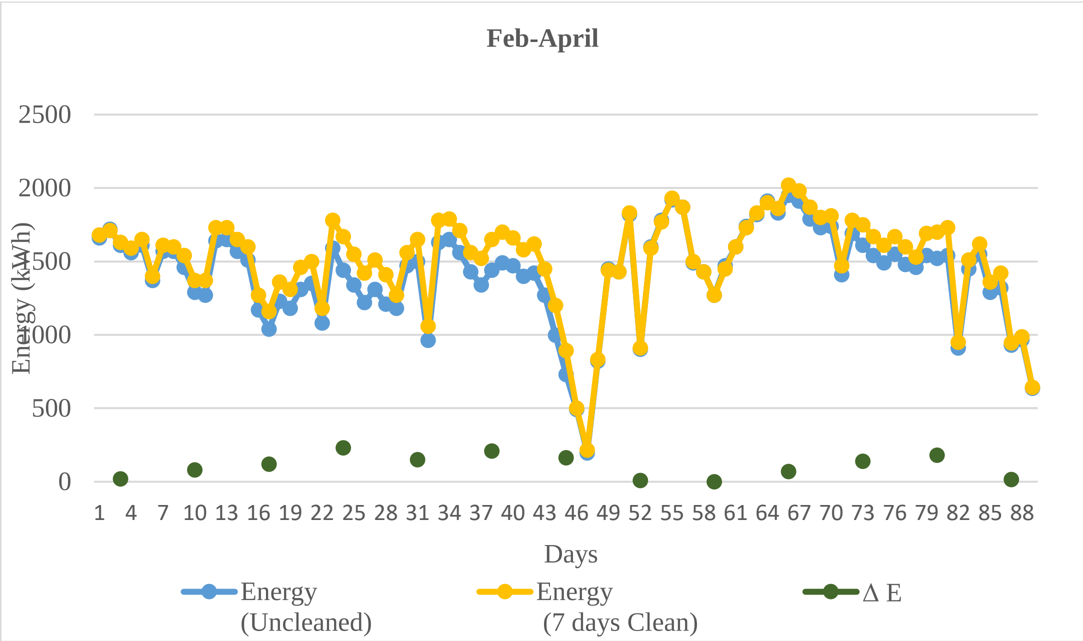

Fig. 5.8 Analysis of February 2023 to April 2023 Duration

The period from May to August can be divided as traditionally having May as the peak summer month, June as the month of onset of the rainy season and July to August as rainy months. There were 11, 16, 17, and 10 nos. recorded rainy days against the rainy-day average of 1.7, 4.8, 9.7, and 10.2 (1991-2020) in May, June, July, and August respectively.

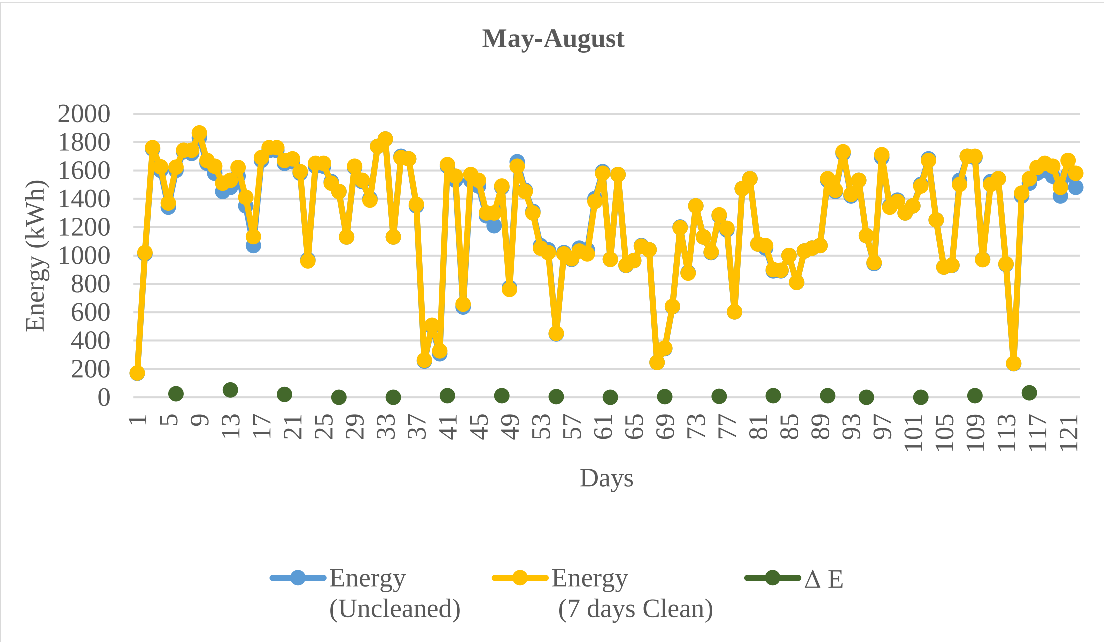

Fig. 5.9 Analysis of May 2023 to August 2023 Duration

Due to sufficiently higher rain episodes during this duration, the curve of energy generation of uncleaned and 7 days cleaned panel are overlapped resulting in an almost constant Δ E trend during this duration. As compared to Fig. 5.7 & 5.8 the curve of Δ E in Fig. 5.9 is flatter due to more rain spells. From the above discussion, it can be concluded that rainfall has a considerable effect on soiling loss.

The variation of soiling loss viz a viz rainfall for the study duration is shown in Fig. 5.10. Based on the above, it can be said that it is prudent to design an optimal cleaning strategy based on rainfall patterns; however, owing to the increase in the uncertainty of the occurrence of rainfall in a particular month as a result of global warming effects, it is challenging to design a cleaning schedule based on natural cleaning by rain. But considering the conservative approach, the optimal cleaning schedule for the worst soiling month in the year will cater to the rest of the months.

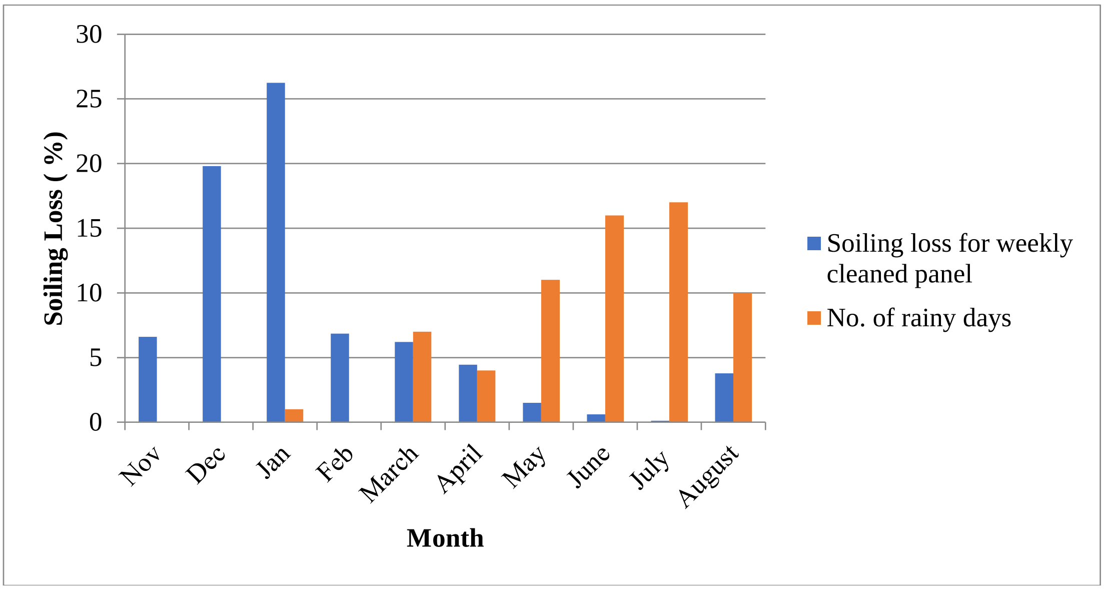

Fig. 5.10 Effect of Rain on Soiling Loss

The monthly variation of energy generation from solar panels has been recorded and plotted in Fig. 5.11. During the study period i.e., from November 2022 to August 2023, it can be observed that the average energy generated by the plant is 4-6 units per day depending on the amount of irradiance and other factors.

The average units are decreasing in the order of increasing gap between cleaning days. The monthly generation is highest for panels cleaned every 7 days. Further, there is no significant difference in the average generation of panels that are cleaned at the duration of 15 and 21 days in comparison to panel that is cleaned at the duration of 7 days.

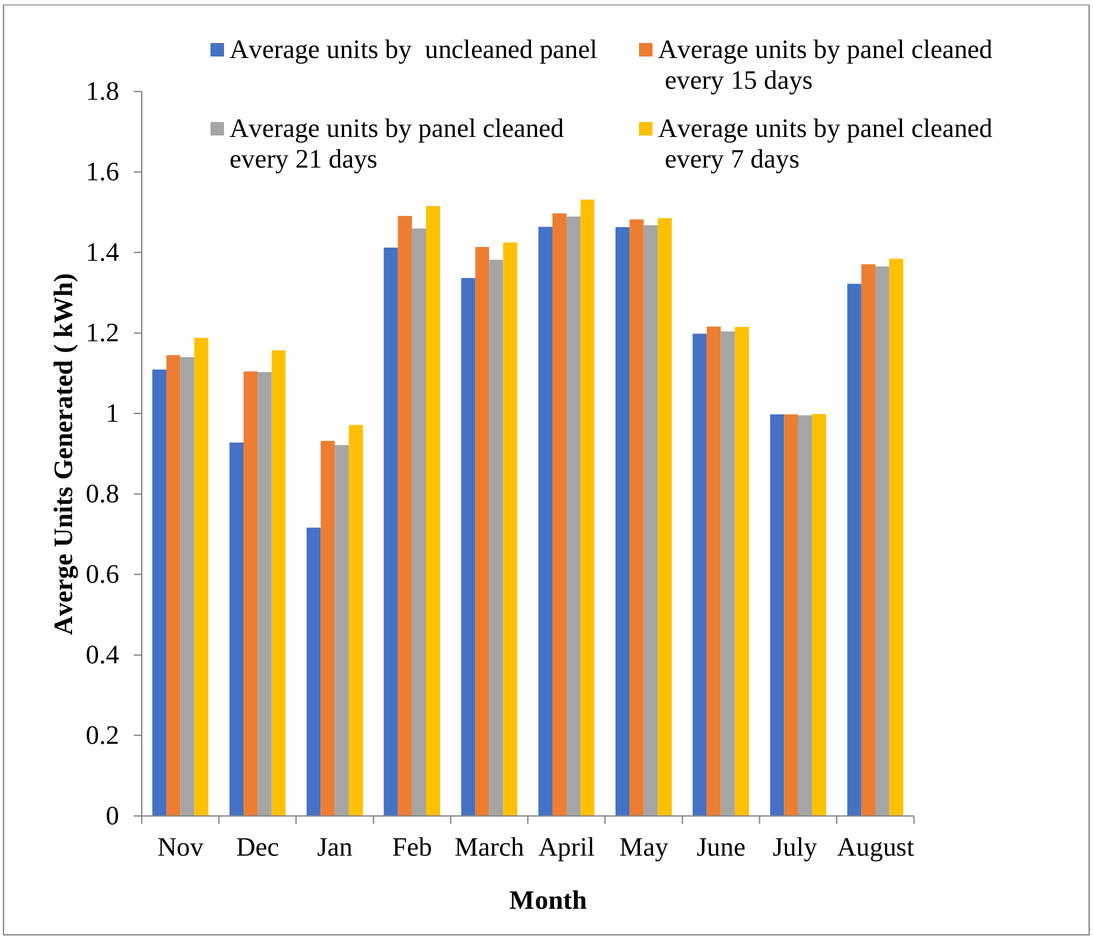

Fig. 5.11 Monthly Variation of Solar Generation of Dusty Panels and Regularly Cleaned Panels

Apart from regular manual cleaning, rain is also an important factor that affects the average generation. The effect of cleaning on average generation is low for months that have a significantly high number of rainy days as shown in Fig. 5.10.

5.4.5 Influence of Dust on Open-Circuit Voltage and Short-Circuit Current

The power, Voc, and Isc of regularly cleaned (7 days) and uncleaned modules on a typical day during the test period (16th January 2023) with a clear day and stable solar radiation are shown in Fig. 5.12, 5.13, and 5.14 respectively. It has been observed that at noon there is a difference of 48W between clean and dusty panels output mainly on account of the difference of short circuit current. At this instant, while open circuit voltage is mostly constant, the short current is 1.6 A less in the case of the dusty panel due to the optical properties of dust where the reflectivity of a dusty surface is lower than that of a clean surface.

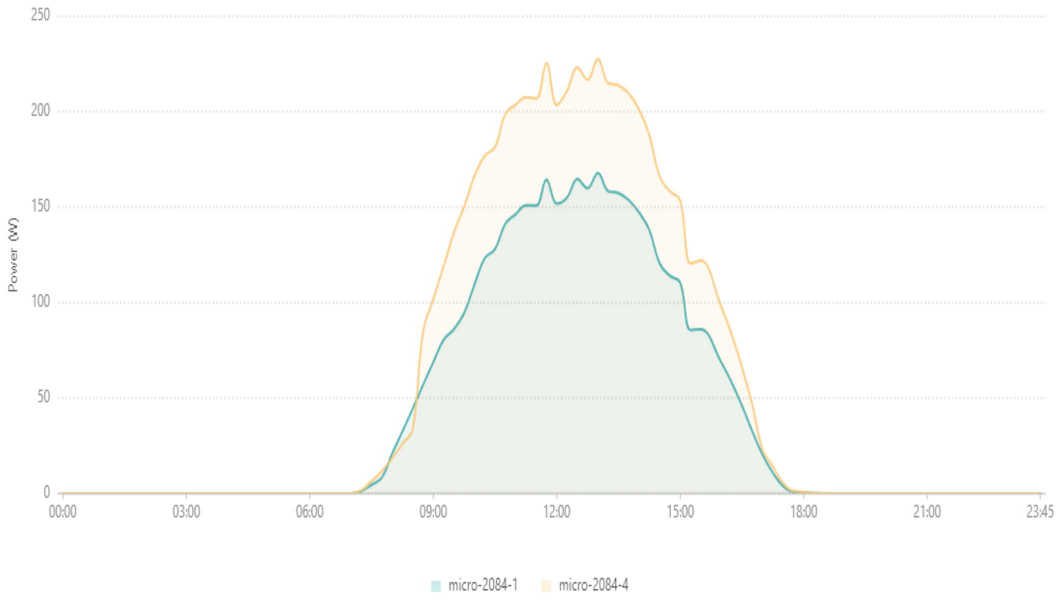

Fig. 5.12 Variation of Power of Regularly Cleaned (7 Days) and Dusty Module

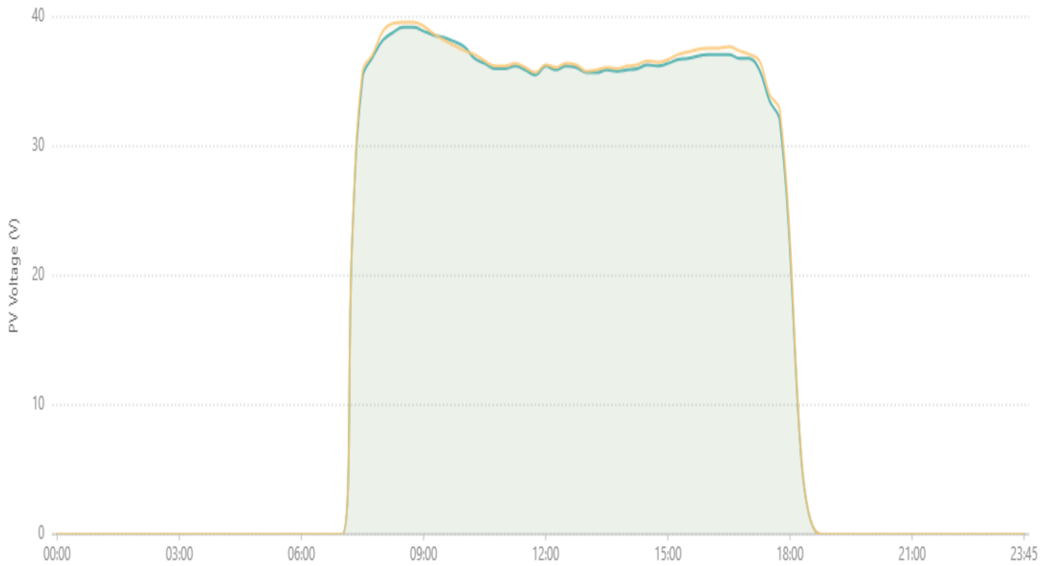

Fig. 5.13 Variation of Open Circuit Voltage of Regularly Cleaned (7 Days) and Dusty Module

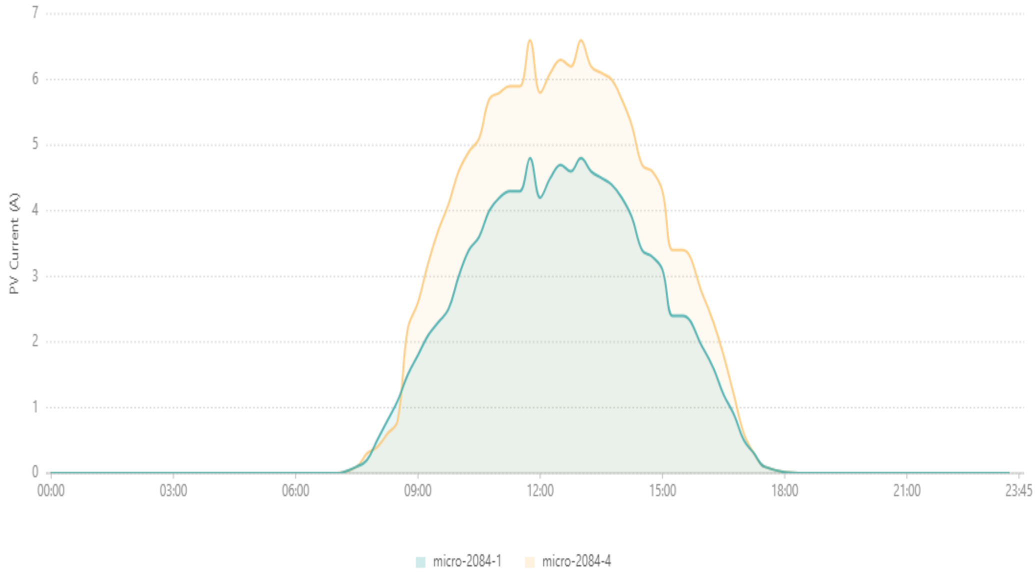

Fig. 5.14 Variation of Short Circuit Current of Regularly Cleaned (7 Days) and Dusty Module

It may be noted from Fig. 5.12, 5.13 & 5.14 that dust deposition does not have a noticeable effect on the open circuit voltage of the panels. However, the effect of dust on the short-circuit current produced by the panels is significant and it has been observed that the clean panel consistently produced a higher current output than the dusty panel.

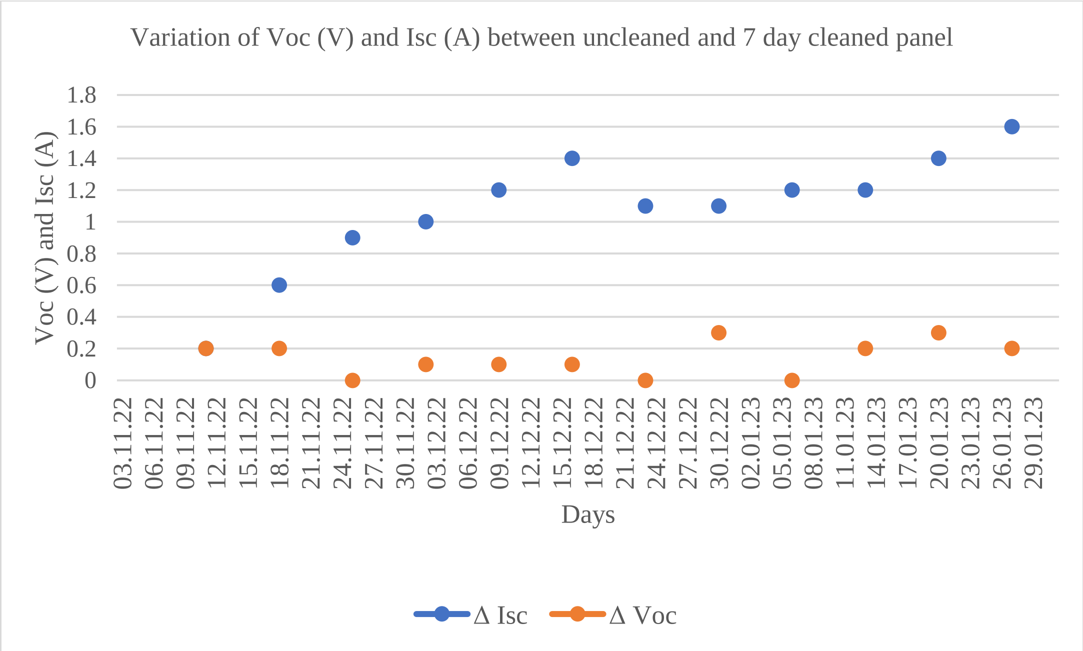

Fig. 5.15 Variation in the Difference of Isc and Voc During the Rain-Free Period

The variation of Voc and Isc of uncleaned and 7 days cleaned panels is significant, particularly during the rain-free period as compared to the rest of the months and the same is plotted in Fig. 5.15. It is observed that the Δ Isc is increasing mainly on account of the decrease of short circuit current of the dusty panel with the dust accumulation while the open circuit voltage remains almost constant for the rain-free period (November to January). The following observations are worth noting:

i. The soiling rates were observed to be higher in winter than in summer and rainy season. The losses are highest in January 2023 (26.25%) and lowest in July 2023 (0.11%).

ii. There seems to be a direct correlation between the number of rainy days and monthly soiling losses. Months with a large number of rainy days have low soiling loss i.e., July while as per the rainfall record, there was only one rainy day in January that too at the end of the month on 31st January 2023, on which 20.4 mm of rainfall was recorded. No rain from November 2022 till January 2023 has resulted in the highest soiling loss due to the accumulation of pollutants from November 2022 till the day of rainfall in January i.e., 31st January 2023.

iii. No significant difference was observed in the average generation of panels that were cleaned at the duration of 15 and 21 days.

iv. The average soiling loss per month during the study period is 7.6%. that amounts to a soiling loss of 0.25% per day.

v. No significant change in panel temperatures has been observed due to dust deposition on the test bed as shown in Table 5.2. During the thermography of panels using the Fluke thermography camera, it has been observed that there is a difference of around 1 degree C when the ambient temperature was 33 degrees C at 4:30 PM on 25.04.2023 between panels that were cleaned in 7 days and those that were cleaned at 14 days, & 21 days and remained uncleaned.

Table 5.2 Thermography Results of Solar Panels

Parameter	Uncleaned Panel	Panel Cleaned every 7 days	Panel Cleaned every 14 days	Panel Cleaned every 21 days
Recorded Panel Temperature (deg. C) at an ambient temperature of 33 deg. C	42.9	42.1	43.0	42.9

5.5 Cleaning of Solar Panels

Cleaning must be done regularly to restore the reduction of the PV panel's performance from soiling. After ascertaining power/ energy losses due to soiling these losses will be minimized as the energy yield from the plant will decide the return on investment made on the plant. The importance of optimizing the cleaning cost lies in the fact that cleaning is both time-consuming and costly. The high pollution levels in Delhi made this task of minimizing loss of energy more challenging. The frequency of cleaning required depends on environmental conditions [155]. Depending on the size of the plant, the site/installation features, the weather, and the possible cleaning costs, various cleaning techniques, such as manual cleaning with water, mechanical dust removal by brushing, blowing, vibrating, ultrasonic, electrostatic, and self-cleaning [156] [157] [158], are used to remove settled dust particles. The methods can be broadly classified as:

i. **Natural Removal of Dust:** The natural removal of dust from the surface of PV panels is carried through rainfall, wind, and gravity. The natural removal methods involve minimum cost but cannot be relied upon owing to their intermittent nature. Rainfall recovers the power output of dusty solar panels; it cannot be depended upon for cleaning as its occurrence highly depends on topography and other environmental conditions of the location. On one hand, rainfall acts as a good cleaning agent when it occurs frequently and abundantly, and on the other hand light rainfall aids soiling due to an increase in the adhesion of dust to the surfaces of PV modules.

ii. **Manual Cleaning:** Cleaning is done through water and the engagement of labour. This method is the most commonly used method for small-capacity plants as it involves a large quantity of water and is not economical for larger-capacity plants and plants having large heights.

iii. **Mechanical Removal of Dust:** Mechanical methods to remove dust are mechanized wiping, blowing, shaking, or vibrating the PV module panel. The wiping is done through the machine to clean the solar module. This method of cleaning through machines requires substantial investment and maintenance of mechanical parts. Similarly blowing of solar panels requires high energy and therefore results in low efficiency.

iv. **Self-Cleaning Methods:** It is done by introducing the superhydrophobic surface like lotus leaves that causes water droplets that fall on the surface to quickly roll off, carrying dust and other particles. While superhydrophilic surfaces like titanium dioxide (TiO_2) are used. TiO_2 under the effect of ultraviolet radiation breaks down organic dust. Then in the next step, due to the super-hydrophilic property, raindrops, rather than gathering in one place, spread over the entire surface and wash away the dust particles [159].

v. **Advanced Methods:** Advanced methods like electrostatic removal of dust, robotic cleaning [160], doping, and modification of this material are mostly in the demonstration and research phases. A substantial amount of research has been done on how dust affects the effectiveness and performance of solar panels. However, limited research has been conducted on the frequency of cleaning solar panels. The choice of cleaning frequency will depend on energy gains that will be achieved vis a vis cost incurred in the cleaning of panels.

5.6 Cost Economics of Cleaning

After quantification of soiling losses, it is important to gauge the effect of losses on various stakeholders. The decision to clean solar panels and let them clean through natural cleaning is a question of cost economics. The savings accrued by regular cleaning in terms of the number of units saved should outweigh the cost of cleaning [161]. The various costs apart from the time involved for cleaning involve the cost of water, labour, consumables, etc. The cost and type of cleaning method vary from place to place. It has been observed from the previous section that regular cleaning of solar panels results in substantial savings. It has been demonstrated that saving of 0.25% per day can be achieved by following every seven days' cleaning schedule in Delhi.

The study on the optimum frequency of cleaning days was conducted by [162] wherein an empirical formula as given in Eqn. 5.4 for the optimal number of days between cleaning cycles is presented

$$N = \sqrt{2P/si\alpha\beta} \tag{5.4}$$

Where N denotes the optimal number of days between cleaning cycles, P is the cost of cleaning, α average loss due to dust, β price of electricity per unit, i is the capacity of the installed PV system and s is no. of sunshine hours. Eqn. 5.4 presented for deriving the optimal frequency of the solar panel cleaning cycle has assumed a linear relation between efficiency and amount of dust accumulation without compromise of accuracy. The above-generalized Eqn. 5.4 can be rewritten as Eqn. 5.5 for rainy ($\boldsymbol{N_r}$) from May 2023 to July 2023 and rain-free periods ($\boldsymbol{N_{rf}}$) from November 2022 to January 2023.

$$\frac{\boldsymbol{N_{rf}} = \sqrt{2P_{rf}/s_{rf}\, i_{rf}\alpha_{rf}\beta_{rf}}}{\boldsymbol{N_r} = \sqrt{2P_r/s_r i_r\alpha_r\beta_r}} \tag{5.5}$$

The experimental values of α for rain-free and rainy periods are 17.55% and 1% respectively and similarly, values of sunshine hours for rain-free and rainy periods are 7.9 and 7.4 hours respectively. The relation between optimal cleaning frequency during rain-free and rainy periods is given by Eqn. 5.6.

$$\boldsymbol{N_{rf}} = 0.23\ \mathbf{N}_r \tag{5.6}$$

This implies that the daily cleaning schedule in a rain-free period is equivalent to a 4.5-day cleaning schedule during rainy periods in terms of soiling loss. The above relation indicates that corresponding to 7-day cleaning in rain-free periods only once per month cleaning is required during rainy months. Since cleaning involves cost on account of labour cost and cost of other consumables and water, a prudent decision can be taken based on the cost of cleaning and savings accrued on account of saving of energy.

5.7 Analysis and Discussion

To meet global energy needs, solar energy is considered a clean energy source that reduces greenhouse gas emissions. The photovoltaic systems are becoming more and more affordable due to advancements in technology. Soiling is one of the major issues that inhibits their usage in a polluting environment. From an economic perspective, solar panels should be cleaned frequently to increase efficiency and achieve maximum gain. In the present study, it has been demonstrated experimentally that the improvement of air quality will improve the utilization of solar energy in Delhi. Rainfall is found to be a major contributor for improving air quality by suppressing the prominent pollutants PM 2.5 and PM 10. Further, this has been corroborated during the analysis of dust samples from the experimental setup where it has been found that deposited particles have a size of less than 2.5 micrometres. Oxygen has the highest chemical concentration followed by silicon, sodium, calcium, magnesium, and carbon in the collected dust samples. The rest of the composition includes aluminium, iron, sulphur, potassium, phosphorus, and zirconium. The dust deposition does have a noticeable effect on the short-circuit current produced by the panels. However, the open circuit voltage usually remains constant.

The soiling problem can be overcome by periodic cleaning of solar panels. Cleaning of solar panels is costly because of the involvement of time and cost hence it is essential to strike a balance between the two. Based on soiling losses the present study also recommends the optimal frequency of cleaning during the experiment period. The result indicates that a daily cleaning schedule in a rain-free period is equivalent to a 4.5-day cleaning schedule during rainy periods. Since energy and climate change are interlinked sectors, this study also provides food for thought to policymakers to adopt emissions controls for the larger interest of the public and society as a whole.

5.8 Concluding Remarks

During the observed period of November 2022-August 2023, the soiling rates generally appear to be higher in winter than in summer and rainy season. The losses are highest in January 2023 and lowest in July 2023. The average soiling loss per month during the study period is 7.6%. that amounts to a daily soiling loss of 0.25% and no significant differences in panel temperatures have been observed due to dust deposition between the cleaned and uncleaned panels. In our study, SEM imaging analysis indicates more concentration of PM2.5 particles. The data obtained from the CPCB portal for DTU also indicates PM 2.5 as a prominent pollutant, thus substantiating the finding in the present study. Based on XRF analysis, the main constituents of the dust particles are oxygen, silicon sodium, and calcium.

CHAPTER 6

END OF LIFE SOLAR PHOTOVOLTAIC PANEL WASTE MANAGEMENT IN INDIA

6.1 Introduction

With the advent of new technologies and products in markets, older products are rapidly becoming obsolete. The volume of waste, particularly, e-waste is growing rapidly. A developing country like India has become a dumping ground, because of waste accumulation not only from waste generated within the country but also from waste being dumped illegally from developed countries [163] [164]. On one hand, India is still grappling with challenges to find solutions for the e-waste problem and on the other hand, with growth and rapid advancement in the deployment of solar energy resources in the country, the chances of solar waste turning into a bigger environmental problem are looming large [165] [166] [167]. Worldwide, the major thrust is on the improvement of production efficiency, and very little or no attention is paid to the slowly but surely increasing photovoltaic (PV) waste problem. India is in the stage of installation of solar photovoltaic panels and no focus is being given towards the impending problem of handling solar waste. The absence of adequate regulations, guidelines and operational infrastructure for photovoltaic waste in the country may lead to waste being inappropriately landfilled or incinerated in a manner that may be detrimental to human health and the environment.

The PV effect involves the conversion of light (photons) into electricity. The complete system of energy generation from the PV system can be divided into two parts viz. the Balance of System (BOS) and PV modules. BOS is a collection of devices that includes an inverter, transformer, wiring, mounting and tracking systems, charge regulators, sun trackers, and batteries. Several studies on PV waste assessment conducted the world over have excluded the BOS wastes and focussed only on the wastes generated from the PV module or panel [168] [169] [170]. Solar PV panels can be broadly classified into three generations: (1) Crystalline Silicon (c-Si) wafer-based (monocrystalline or polycrystalline); (2) thin-film (amorphous silicon, cadmium telluride, copper indium gallium selenide - CIGS); and (3) Concentrator Photovoltaic (CPV) and emerging technologies solar panels (dye-sensitized solar panels, organic solar panels, and hybrid panels). Out of these different types of PV panel modules, the most prevalent module types are wafer-based (monocrystalline and polycrystalline) and thin-film. Wafer-based silicon panels in comparison to thin film solar panels have higher conversion efficiency and are the most widely used solar panels commercially. Wafer-based PV technology accounted for nearly 95% of the total production in the year 2019 [171] Fig. 6.1 shows the general structure of the crystalline Si-wafer-based PV module.

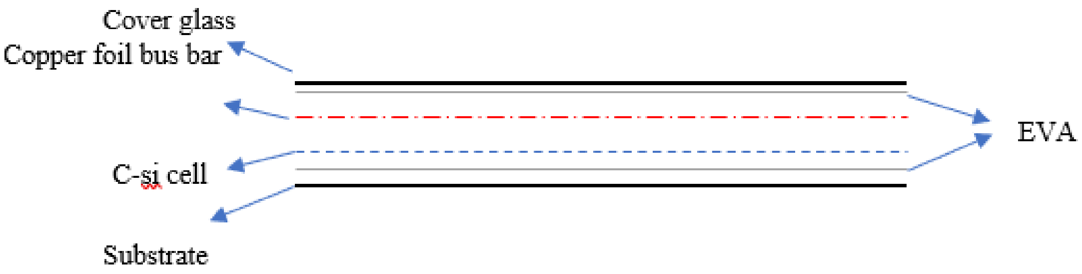

Fig. 6.1 General Structure of C-Si Wafer-Based PV Module

The modelling in the current study is done based on the rate of installation of crystalline technology since it is anticipated that crystalline Si-wafer-based technology will dominate the solar PV panels market share in the next decades.

It is revealed from the literature review that most of the studies are concentrated particularly towards solar PV waste estimation, life cycle, and economic assessment of PV panels, but still, there are considerable gaps in these studies, as the success of the EoL solution of solar PV panels depends on the robustness of local regulatory and policy framework and overall participation of various stakeholders viz. original equipment manufacturers, solar PV system installers, consumers, recyclers, and various government organizations. None of the studies conducted so far has highlighted the enormity of the impending solar PV waste problem in India. In comparison to the available scattered literature on solar PV waste estimation in India, the present study was conducted after the COVID-19 pandemic and therefore also highlights the effect of the COVID-19 pandemic on waste volumes. India is undergoing a clean energy transition. The government is implementing various programmes and regulatory measures into place to raise the percentage of renewable energy sources in the overall mix of electricity. Among different renewable energy sources, significant capacity addition in solar energy in the form of rooftop and utility-scale solar installation has been made. Solar power from an energy requirement point of view promises a bright future for India, but behind the gleam is a growing mountain of e-waste. With the current growth rate of solar PV, the solar waste problem will turn into a serious environmental problem in the next decades unless addressed at this stage. The country lacks even conventional recycling facilities to separate glass and aluminium frames from the modules.

The present study is undertaken to estimate the volume of solar PV waste in India, particularly at the time when the country is undergoing a massive solar capacity expansion programme and also presents an environmentally benign strategy to policymakers for the handling of solar waste using LCA methodology. The role of the avoided burden approach due to recycling of materials from the point of view of circular economy prospects has been discussed. Additionally, the breakups of the amount of materials that can be recovered along with environmental gains associated with their replacement from virgin material are also discussed.

6.2 Methodology Adopted for PV Waste Projection

From the perspective of PV waste determination, the complete life cycle of a solar PV module can be divided into the following stages:

i. **Processing and Production Stage:** In comparison to polycrystalline panels, the making of monocrystalline panels results in the production of more waste since they are made from silicon ingot slices - leaving offcuts, etc. However, this waste can be further utilized to make polycrystalline or multi-crystalline PV modules. In thin-film silicon panels there is a reduction in the volume of material needed as they are made by spraying a thin layer of silicon onto the surface, so has the potential to reduce impacts and waste. Production waste is the most easily managed waste as manufacturers are well equipped to handle such waste and production waste is not a societal waste management problem [172].

ii. **Transportation Stage:** Panels may get damaged due to their transportation from the manufacturing to the installation site. The major reason is the ill-handling of PV modules during the loading and unloading of PV panels.

iii. **Operation Stage:** Faulty installation practices along with extreme weather conditions like hailstorms, floods, cyclones, etc. may also result in the generation of solar waste during the initial and active life cycle of solar panels.

iv. **End-of-Life Stage:** PV modules reach their End-of-Life (EoL) stage when the overall power output of modules drops below 80% of the initial quoted value at the time of manufacture [173]. This stage will contribute to maximum waste generation typically after the actual life cycle of 25-30 years of the solar PV module [79] [81] [84] [172] [174] [175]. The exponential growth in the installation of PV capacity in recent years means there will also be a rapid increase in the number of panels reaching their EoL stage [176]. Fig. 6.2 shows various stages of solar PV waste generation during the complete life cycle of the solar PV module. The cycle shown in the continuous line is an open cycle, however, if dotted lines are incorporated, the use of raw materials is not only minimized but also burdens on the environment are also minimal. Currently, in the absence of any significant waste recycling techniques, there is a high dependency on the supply of raw materials from natural resources during the production stage.

PV panel waste volume will increase along with the PV deployment rate. One of the easiest ways to predict waste streams is by considering a fixed loss scenario. This scenario assumes that after the lifetime of the PV panel (25-30 years), it will be discarded. On the other hand, the cumulative PV waste generation can be obtained more accurately for regular-loss and early-loss scenarios by the multiplication of the probability distribution function with the weight of panels installed in a particular year.

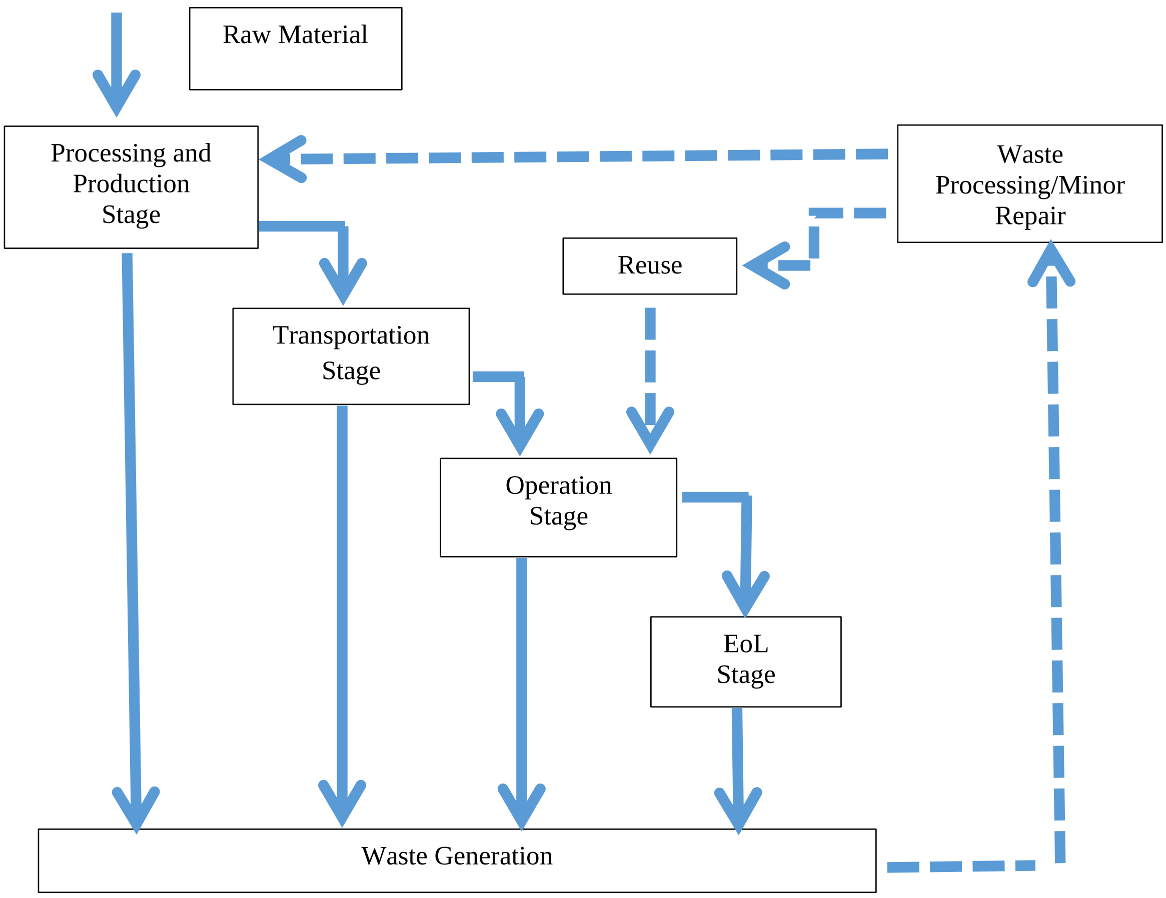

Fig. 6.2 Various Stages of Solar PV Waste Generation

Despite every effort made in the present study to predict the solar waste data and its effect on the environment with accuracy, various assumptions have been taken throughout the study that may affect the outcomes. The probable sources of some of the uncertainties are:

i. **Uncertainty Due to Projected Solar PV Capacity:** The present solar PV growth rate forms the basis of 339 GW solar PV cumulative installed capacity by 2040 in the BAU scenario and the basis for 395 GW solar PV cumulative installed capacity by 2040 in an ambitious scenario is based on estimations provided under draft national energy policy [177] report. Both these estimations introduce uncertainties in final PV waste figures as in the BAU scenario the installed capacity figures up to 2021 are extrapolated to obtain estimated values by 2040. In an ambitious scenario, it is difficult to judge the reliability of estimations provided in said study. The estimations provide indicative figures of waste volumes that will be generated. Further, a series of Covid-19 pandemic waves and other market disruptions have also created uncertainty in capacity additions.

ii. **Uncertainty Due to Tonnes Per MW Ratio:** With the improvement of technology PV modules are becoming lighter and lighter. The mass-to-power ratio till the year 2040 has been predicted from past data fitting to an exponentially decreasing curve. In the absence of the availability of year-wise panel weight data in the public domain, the past data in the present estimation has been obtained from a leading solar PV manufacturer in India through e-mail correspondence.

iii. Uncertainty Due to Cut-Off Point for EoL: It is not necessary panels will become obsolete after 25 years and in many cases, it has been observed that the PV module would still deliver enough power after their end-of-life period of 25 years. This will be more predominant in the case of solar PV panels installed on the rooftops of residential buildings. This will introduce uncertainties in the figure of waste streams.

iv. Uncertainty Due to Solar Technology: This study takes into consideration that c-Si technology will remain and continue to dominate the PV market in the coming years. Any significant change in the market share of c-Si technology will affect the solar waste estimation projection and LCA results.

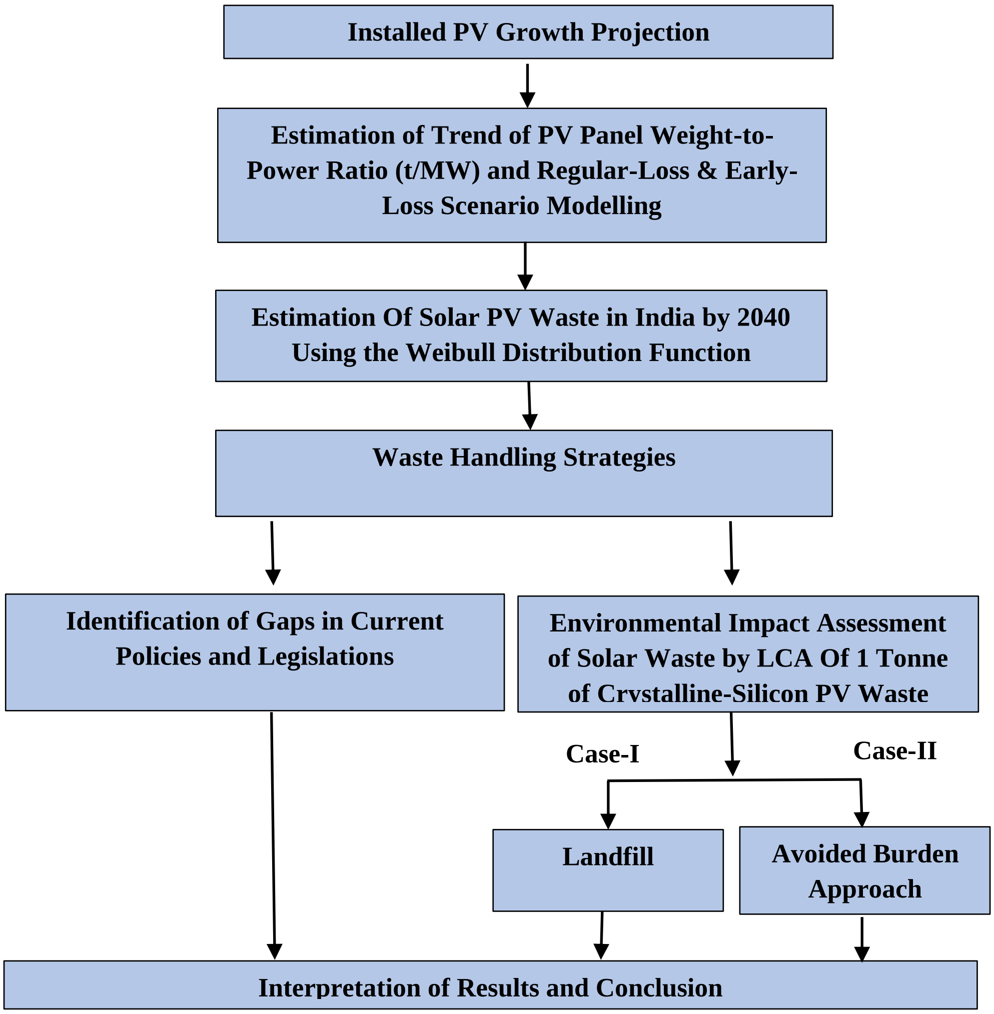

Fig. 6.3 Description of Methodology Adopted

A further change in the proportions of various raw materials in the PV module will affect the mass percentage of the recoverable from the recycling process. In this study, the methodology as shown in Fig. 6.3 has been adopted.

6.2.1 Solar PV Waste Forecasting

Without waiting for the end of life of solar cells which typically varies from 25-30 years the slowly and surely increasing problem of solar waste can be best addressed by estimating solar waste using a mathematical probability distribution function based on its projected growth. In India, significant solar PV installation started near the year 2010, the corresponding PV waste due to regular loss scenario should be generated by 2035–2040 [178] and it can be said that the critical point from a waste generation point of view, will reach by 2040. To estimate the solar PV waste in India firstly, futuristic PV installed capacity is projected under two scenarios i.e., the Business as Usual (BAU) scenario and the ambitious scenario. Secondly, a tonnes/MW projection to estimate the weight of waste generated is carried out. Finally, mathematical modelling using Weibull distribution is carried out to predict waste volumes.

6.2.2 Installed PV Growth Projection

In India, the cumulative capacity of solar PV installation as of June 2024 is 85 GW compared to 10 MW in 2010 [4] [179]. With the BAU scenario, cumulative solar installed capacity will reach around 339 GW by 2040. The genesis of the ambitious scenario is the numbers provided by NITI Aayog given under the draft national energy policy [177]. The anticipated cumulative capacity at the end of 2040 will be 395 GW refer to Fig. 6.4. The anticipated maximum solar capacity of India is 750 GW [98], therefore even if the ambitious scenario is considered; only approximately 50% of the maximum solar capacity of India will be achieved by 2040. These anticipated projections will form the basis for the estimation of solar PV waste.

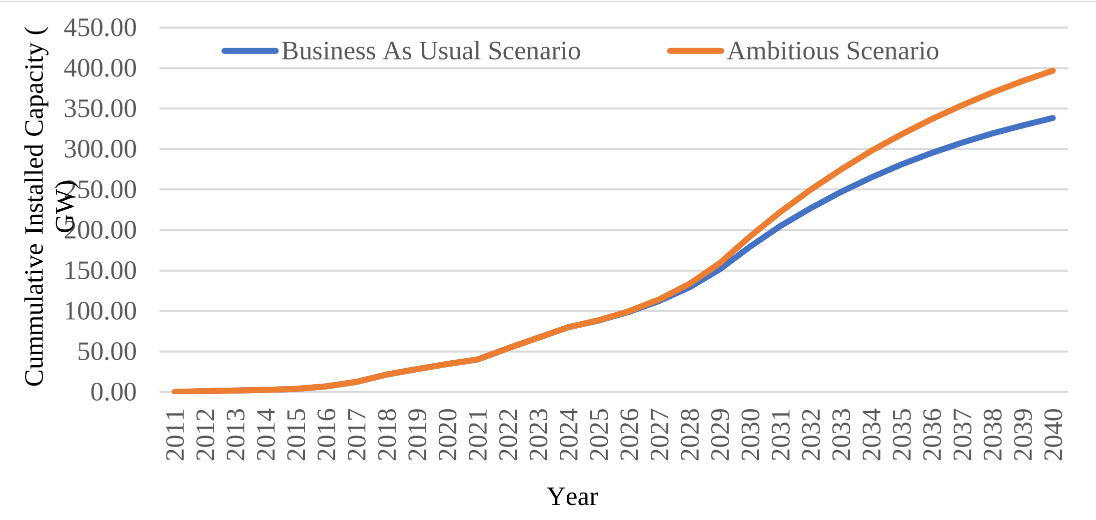

Fig. 6.4 Solar PV Growth Projections

6.2.3 Tonnes/MW Estimation

Waste estimation depends on the weight of the panel being used for installation. The advancement of technology has resulted in thinner frames, glass layers, and wafers along with improved efficiencies thereby resulting in lighter solar panels in other words given the same weight of the panel, more wattage can be accommodated now. The factor t/MW or kg per watt depends on the type of solar technology, size & weight of the panel, solar cell efficiency, and other characteristics of the panels. Earlier studies across the world have taken this factor in the range of 90-100 t/MW [180] [181]. However, in the present study, no constant factor for t/MW has been taken rather its value has been extrapolated, and thus values are more reflective of the expected future weights of installed solar PV panels. The major challenge encountered in obtaining this information from eco-invent or from the datasheet of solar modules is the lack of availability of data pertaining to the weight of the PV model vis-a-vis its manufacturing year. Therefore, in the present study, the information about the yearly variation of t/MW of one of the major solar PV manufacturer companies in India i.e., Waaree Renewable Technologies Limited has been obtained via correspondence through email and is tabulated below in Table 6.1:

Table 6.1 Variation (t/MW) of Waaree Solar Panels

Year	Weight to Power Ratio (t/MW)
2016	74.02
2017	72.05
2018	70.13
2019	68.26
2020	66.44
2021	64.67

The obtained data have been fitted appropriately to an exponentially decreasing function given by Eqn. 6.1.

$$Mass\ to\ power\ ratio\ \left(\frac{t}{MW}\right) for\ \ i^{th}\ year = A.e^{-(i/B)} \qquad (6.1)$$

Where A = 83.855 t/MW, B (exponential time constant) = 47.62 and the value R^2 corresponding to the coefficient of determination of fitting has been taken as 0.97.

6.2.4 Mathematical Modelling Using Weibull Distribution

Solar module failures like failure in other equipment, sub-systems, or components follow the “bathtub” curve i.e., most common failures occur near the beginning and near the end of the component’s lifetime. The three main PV panel failure phases are 1. Infant mortality failure, 2. Midlife failure, and 3. Wear-out failure [182]. Fig. 6.5. shows these failure phase of solar PV modules. Infant mortality occurs at the commencement of the working life cycle, and midlife failures of PV occur from five to eleven years after installation. Further, wear-out failures like delamination, occur from after 12 years of installation to 25-30 years i.e., at the end of the lifetime of PV modules [172].

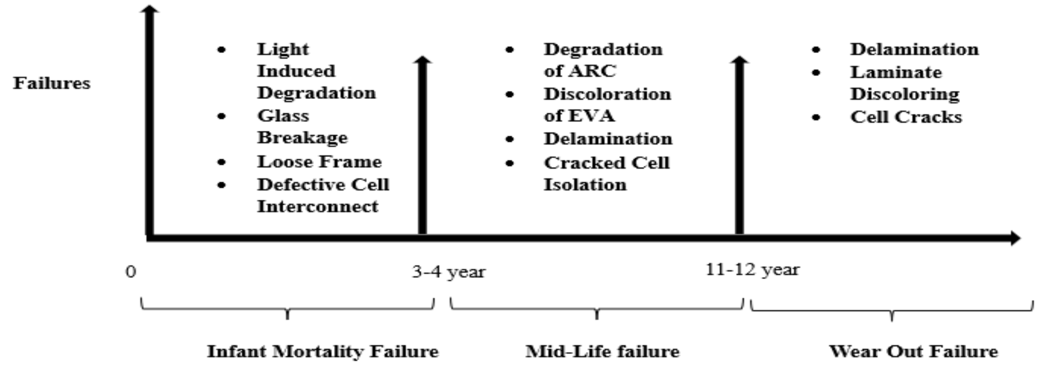

Fig. 6.5 Failure Phase of Solar PV Modules

The anticipated lifetime of PV modules spans several decades in the range of 25-30 years. Device lifespan is the amount of time a device operates as intended, in accordance with design standards, and under predetermined circumstances, before failing. Device life expectancy typically follows a probability distribution. The materials used for manufacturing solar PV cells and design are continually changing to reduce the levelized cost of energy and the researchers cannot wait for the end of the anticipated life of 25-30 years to identify the failure modes and mechanisms. In the present study for carrying out failure and reliability analysis of solar modules, Weibull statistics have been utilized. Weibull statistics is one of the most widely used lifetime distributions in reliability engineering and is used to assess product reliability, analyse life data, and model failure time. Weibull models can include up to three parameters: shape (α), lifespan or scale (δ), and failure-free life or location (θ). In a two-parametric Weibull model, the location parameter (θ) is set to 0. The probability density function can be written as given in Eqn. 6.2 [183]:

$$f(x) = \frac{\alpha}{\delta}\left(\frac{x-\theta}{\delta}\right)^{\alpha-1} e^{-\left(\frac{x-\theta}{\delta}\right)^{\alpha}} \tag{6.2}$$

The Weibull function for reliability can be deduced from Eqn. 6.2 and is given by Eqn. 6.3 as:

$$R(x) = e^{-\left(\frac{x-\theta}{\delta}\right)^{\alpha}} \tag{6.3}$$

The Weibull failure rate function i.e., $\lambda(x)$ is the ratio f(x) to R(x) and is given in Eqn. 6.4 as:

$$\lambda(x) = \frac{f(x)}{R(x)} = \frac{\alpha}{\delta}\left(\frac{x-\theta}{\delta}\right)^{\alpha-1} \tag{6.4}$$

Thus, to estimate the failure rate over time, the parameters α and δ need to be determined.

The above Weibull cumulative distribution function can be transformed into a straight-line equation form i.e., Y=mX+b: [183] as given in Eqn. 6.5.

$$F(t) = 1 - e^{-(\frac{t}{T})^{\alpha}} \tag{6.5}$$

Where, t = time in years and T = average lifetime.

The shape parameter α controls the typical S shape of the Weibull curve and describes how the failure rate changes over time. If α < 1, the failure rate decreases with time and is commonly associated with infantile failures or early life failures. If α =1 means the failure rate is constant. If α > 1 the failure rate increases with time and is associated with failures related to mechanical wear-out failures. Different studies the world over have taken different values of the average lifetime of solar panels varying between 25-30 years. An overview of the value of the average lifetime reported in various studies is given in Table 6.2. The average lifetime of 25 years is taken in the present study based on the Ministry of New and Renewable Energy regulations [174].

Table 6.2 Values of the Average Lifetime of Solar Panels Reported in Various Studies

Region	**Global** [172]	**Europe** [175]	**Italy** [184]	**Mexico** [185]	**Australia** [84]	**India (Present Study)**
Average Lifetime (Year)	30	25	25	30	30	25

The shape factor α determines the probability of regular-loss and early-loss scenarios during the panel life cycle. The present study uses 2.4928 and 5.3759 as the values of shape factors (α) for early-loss and regular-loss scenarios respectively refer Fig. 6.6 [182] [186] [187].

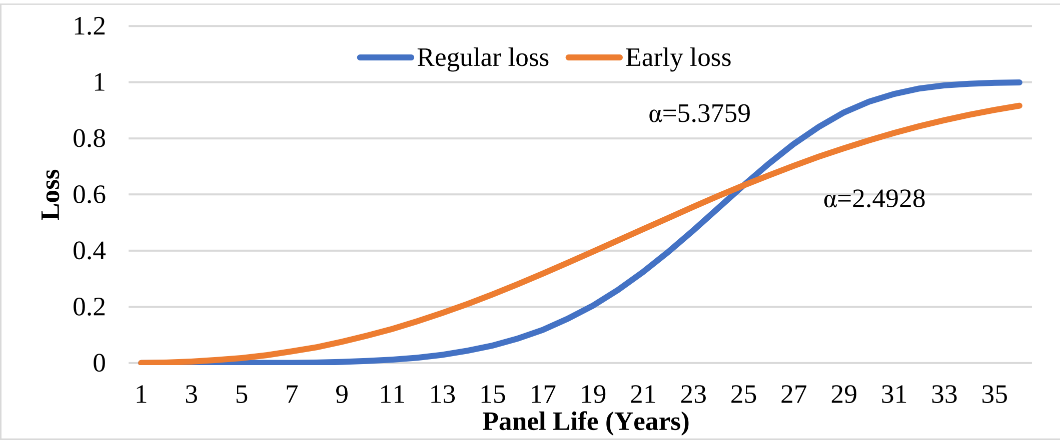

Fig. 6.6 Weibull Curve for Early Loss and Regular Loss

6.3 PV Panel Waste Projections: Analysis and Comparison with Other Studies

India has set a target to meet its 50% cumulative electric power installed capacity from non-fossil sources by 2030 at the 26th session of the Conference of the Parties 26 in Glasgow, United Kingdom. The COVID-19 outbreak affected the solar industry sector at a time when the country's solar project execution was at its peak.

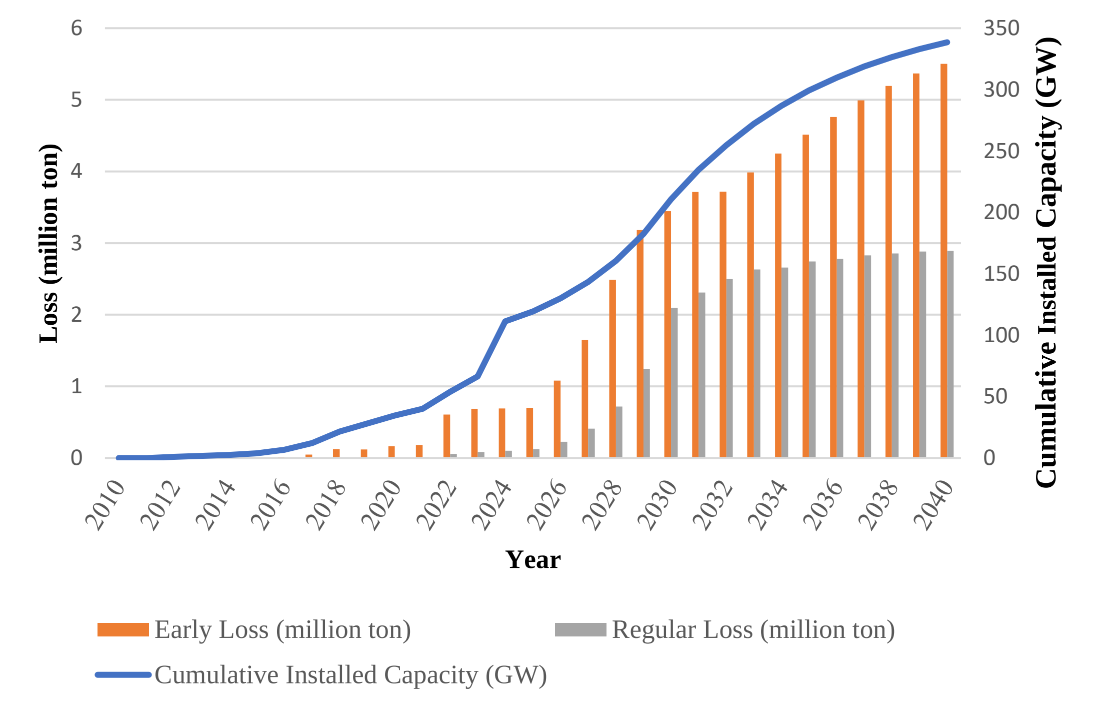

Fig. 6.7 Estimation of PV Panel Waste Using Early and Regular Loss Scenarios for India

India's installed solar capacity suffered a 56% decline in the calendar year 2020 as compared to 2019 [188] mainly due to the disruption of supply chains, workforce availability, and a brake on solar equipment imports from China. The fact is evident from the dip in installed capacity during the year 2020-2021 as shown in Fig. 6.7. COVID-19 derailed India's ambitious target of 175 GW of renewable energy by 2022. The COVID-19 pandemic has posed tough challenges by impacting the pace of development and commissioning of renewable energy projects. Accordingly, several steps were initiated like an auction of new tenders, extensions of deadlines, advising states to maintain the sanctity of agreements, and ensuring certainty in supporting regulations for renewables to bring the sector back to the path of recovery [189]. Based on cumulative installed capacity by 2040 under BAU, the cumulative PV waste generation due to early and regular loss scenarios are 5.7 million tonnes and 4.24 million tonnes respectively and under the ambitious scenario by 2040, the cumulative PV waste generation due to early and regular loss scenario is 7.36 million tonnes and 5.96 million tonnes respectively.

India's solar waste prediction was also carried out by the International

Energy Agency [92] [172]. IEA study [172] predicted solar PV waste could average 50,000-320,000 tonnes by 2030, possibly ending in 4.4 to 7.5 million tonnes by 2050. Similarly, another study by Pankadan et al [92] predicted 0.4 million tonnes and 0.038 million tonnes of PV waste generation due to early and regular losses, respectively for India by 2030, and 7.99 million tonnes and 3.61 million tonnes of waste generation due to early and regular losses, respectively by 2050. The main reason for the variation of waste volumes in the present study and studies conducted earlier for India is the variation in the projection of installed capacities since the present study includes the disruptions of the solar market due to COVID-19 secondly present study assumes a 25-year lifetime for solar panels, in contrast to 30 year lifetime in IEA study [172] and 25-30 year in the study conducted by Pankadan [92]. Thirdly present study uses power-to-weight ratio trends of an Indian solar manufacturer i.e., Waaree for the period 2015-2021 while the IEA study uses panel datasheet of leading producers of the world for the period 1980-2013 and the other study is silent on values of power-to-weight ratios.

6.4 Waste Management Guidelines: National and International Scenario

India notified the E-waste management rules, 2016 [190] and as compared to the E-waste (management & handling) rules, 2011, the key difference is the provision of Extended Producer Responsibility (EPR) to ensure that electronic products are recovered for safe recycling. However, the rules were silent about solar PV waste and there is always a risk that waste PV modules end up in uncontrolled or not environmentally sound disposal operations such as uncontrolled or illegal landfills or open land [191]. However, on 2nd November 2022 the Ministry of Environment, Forest and Climate Change (MoEFCC) notified the E-Waste (Management) Rules, 2022 to include the management of solar PV modules panels/ cells. As per these rules, every manufacturer and producer of solar photovoltaic modules or panels or cells shall ensure registration on the portal and have to store waste generated up to the year 2034-2035 as per the guidelines laid down by the Central Pollution Control Board. Further recycling of solar photovoltaic modules or panels or cells has been mandated for the recovery of material.

Despite this, India will likely face serious challenges regarding mechanisms to address the management of solar PV waste and its disposal in the near future as solar power waste management is a neglected sector and follows an unregularized, unscientific, and informal approach [192]. In a developing country like India, the model commonly found for addressing waste is based on a linear model, in which different extracted raw materials are processed to make the end product, then transported to the user site, and finally discarded as waste at the EoL cycle of the product. However, in a circular model, waste streams by different processes are converted into basic raw materials thus a continuous closed cycle will be initiated by bringing back waste to the material flow cycle. Lack of incentives, strict compliance with regulatory policies, and knowledge about the value of extractable materials and their corresponding environmental impacts are major hindrances in the safe disposal of PV waste material. Globally, it has been estimated that only 10% of the total solar PV waste is currently recycled which indicates a massive gap in the availability of the operational infrastructure [193]. With prodigious growth, the problem of solar PV waste management is inching slowly to an alarming stage. The list of developments in some major regions of the world is summarised below [92] [194] [195] [196] [197].

i. **United States of America**: There are no specific federal laws or regulations so at present only laws dealing with general waste are applicable however, some states like Washington, and California have developed their regulation or laws for PV module utilization and recycling. Certain businesses, including "Solar World" and "We Recycle Solar," have taken the lead in developing their framework for material recovery and recycling.

ii. **European Union**: The First Waste Electric and Electronic Equipment (WEEE) directive of 2003 was silent on tackling PV waste. However, modified WEEE include EoL management of PV modules and as per the latest WEEE directive, PV manufacturers will have the main liability for the costs of collection, handling, and treatment of PV waste irrespective of the location of the manufacturing facility. The modified directive is applicable to all European Union members. Additionally, the EU established the non-profit group "PV Cycle" to help European PV firms comply with rules and manage waste.

iii. **China**: China is the biggest manufacturer and user of photovoltaic panels worldwide. The proper disposal and recycling of panels have been addressed by the Chinese government through a variety of legislative initiatives and laws. The National Solid Waste Law controls the type and quality of waste that enters the nation. Other programs include the Producer Responsibility Extension System, which mandates that manufacturers to design recyclable products, establish buy-back programs, pay for recycling, and keep detailed records.

iv. **Japan**: Along with voluntary guidelines, Japan has enacted many significant laws and regulations to regulate the treatment of EOL PV waste. Resource Recycling Act is a key legislation that establishes precise guidelines for the collection, transportation, and recycling of EOL PV modules. While the Japan Photovoltaic Energy Association (JPEA) recycling guidelines are a key element of Japan's voluntary approach.

v. **India**: In India, earlier there was no central regulation and therefore PV waste was treated under general waste regulations that have limited scope. The E-Waste (Management) Rules, 2022, which include the management of solar PV modules, panels, and cells, were recently announced by the MoEFCC wherein, it will be mandatory for recyclers of solar photovoltaic modules, panels, or cells to recover materials according to the Central Pollution Control Board's guidelines. This will not only in the recovery of valuable materials from the waste but also result in the reduction of the environmental impact of solar panel waste management.

6.5 Strategies for India

Until the revision of E-Waste (Management) rules both the Indian government and the Indian solar industry followed the E-Waste Management Rules 2016 as a reference law. For example, the guidelines of Solar Energy Corporation of India Limited (SECI) for setting up grid-connected solar PV plants state that “the solar power developer will ensure that all solar PV modules from their plant after their ‘end-of-life’ (when they become defective/ non-operational/ non-repairable) are disposed of in accordance with the “e-waste (management and handling) rules, 2011” notified by the government and as revised and amended from time to time.” [198] . Thus, there is significant scope for a regulated approach to solar waste management that will lead to environmental benefits and enhance the prospects of the circular economy by substituting virgin material manufacturing with recycled material. Hopefully, strict compliance with the revised E-Waste (Management) Rules 2022 will help in tackling the solar PV waste problem. The following section discusses the probable waste mitigation strategies for India along with their limitations. Fig. 6.8. represents probable solar waste mitigation strategies.

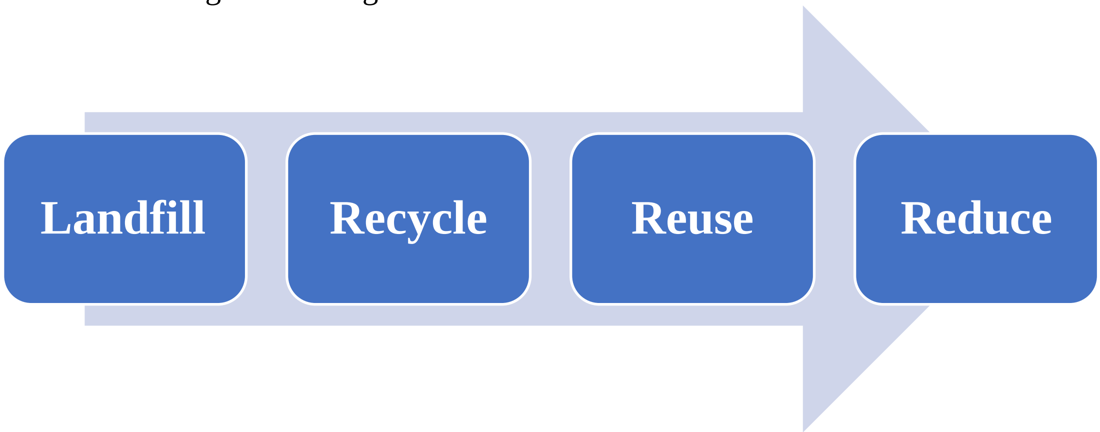

Fig. 6.8 Probable Solar Waste Mitigation Strategies for India

i. **Reduce:** The thumb rule for handling waste is first to reduce, reuse, and then recycle. Solar waste volumes can be considerably reduced by improvement in the design of products and manufacturing processes. The use of various hazardous materials like lead, cadmium, and selenium can be limited by extensive research and development. Similarly, the use of silver can be avoided due to advancements in inkjet and screen-printing technologies. New and innovative techniques in printing and pastes have been projected to reduce silver consumption from 0.16 g/Wp in 2005 to less than 0.1 g/Wp in 2020 [199]. Efforts should be made to design a product with fewer amounts of hazardous materials. Careful handling of modules during transportation and operation stages will also result in a decrease in waste volumes.

ii. **Reuse:** Both reusing and recycling strive to achieve a common goal but are different terms that are not interchangeable. Reuse is a means to prevent waste streams from entering landfills. It is the action or practice of using an item, whether for its original purpose or to fulfil a different function thus increasing the occupational well-being of citizens by taking useful products discarded by those who no longer want them and providing them to those who do. Further, recycling results in keeping waste materials out of the landfill by “collecting, segregating, processing, and manufacturing collected goods into new products” [200]. The flaws and imperfections discovered during the early phase of a PV panel’s lifecycle can be easily handled by imparting specific training and skills on PV panel repairs. In addition to extending the lifespan of PV panels, this will create a market where repaired PV panels can be sold at a lower market price than new or used panels. A second-hand market can be developed for repaired panels and for panels that have lived up to their nominal lifetime, after necessary repairs.

iii. Recycle: Not only solar panel production is a highly energy-intensive process but also the presence of hazardous materials like lead, and cadmium in the end-of-life panels can cause significant pollution and health issues if discharged into the environment. Therefore, the recycling of waste solar panels can reduce energy waste and environmental pollution [201]. In the comparison of P–V and I–V characteristics of old, recycled, and new PV modules, it is observed that the characteristics of the recycled module are at par with the new module [202]. Recycling constituent materials of solar PV back to manufacturing will cut down imports from natural resources. There is a scope for reduction in the EoL solar PV waste in the range of 60%-90% due to the high potential of recyclability rates of the constituent solar PV materials [80] [185] [203].

Based on the above discussions, dedicated PV panel recycling plants need to be created, even though waste recovery models are not economically viable at the present stage owing to low to moderate values of PV waste generation. The government may consider incentivizing the waste recovery units for a few initial years. The treatment of solar PV waste requires significant importance not only from environmental benefits arising from the treatment of waste but also has economic significance since the recovery of materials can be used as raw material during different stages of solar PV panel production. The solar PV waste recycling industry can be considered a secondary mining industry.

iv. Landfill: Improper waste disposal at landfill sites as the case with e-waste disposal will result in the leaching of lead and cadmium into groundwater and will result in further worsening groundwater quality. Leaching of lead may result in reduced growth of flora and fauna, destruction of habitat, and adverse health hazards on the nervous, kidney, immune, and reproductive function systems in the human body. It may also result in impaired brain development in children. Cadmium is a highly toxic carcinogen and is linked to lung, human prostate and renal cancer [167]. Landfill as an option for solar waste disposal is the easiest to implement but not only it results in the loss of valuable materials but also results in economic loss and should be assigned the lowest priority while designing solar waste disposal strategies. The improper treatment of PV waste may result in the loss of potentially conventionally reusable materials like aluminium and glass which have a share of 88% in terms of weight [204]. Not only this, but the landfill will also result in the loss of rare and/or critical metals (e.g., silicon metal) and precious metals like silver, a well-known conductor, though found in a small quantity. WEEE directive based on EPR encourages resource efficiency through reuse, recycling, and minimising the dumping of waste in landfills [205].

Apart from the ‘3Rs’ concept of sustainable waste management, i.e., Reduce, Reuse, and Recycle, a multi-sector and multi-stakeholder coordinated approach among various ministries like MNRE, MoEFCC, Ministry of Power (MoP), SECI, solar PV manufacturers, and other stakeholders is required. The enforcement of extended producer responsibility legislation will cover collection, recovery, and recycling of solar PV modules is the need of the hour to tackle solar PV waste challenges.

6.6. Environmental Impact Assessment using LCA Analysis

The Life Cycle Assessment (LCA) is an objective procedure for assessing the energy and environmental loads related to a process or activity, carried out by identifying the energy and materials used, and the waste released into the environment. According to the ISO 14040 series, the analysis of LCA consists of four consecutive steps as shown in Fig. 6.9 [206]. An LCA study is initiated by defining the goals & scope, the functional unit, and the system boundary of the study in the first step. Identifying the inputs and outputs related to each stage of a product's life cycle is the next step, referred to as a Life Cycle Inventory (LCI). In the Life Cycle Impact Assessment (LCIA) step, the evaluation of potential impacts based on the inventory is carried out. The results of the impact assessment are analysed in the final step known as the interpretation phase. The analysis of the data completeness, sensitivity, and consistency is also part of the interpretation step.

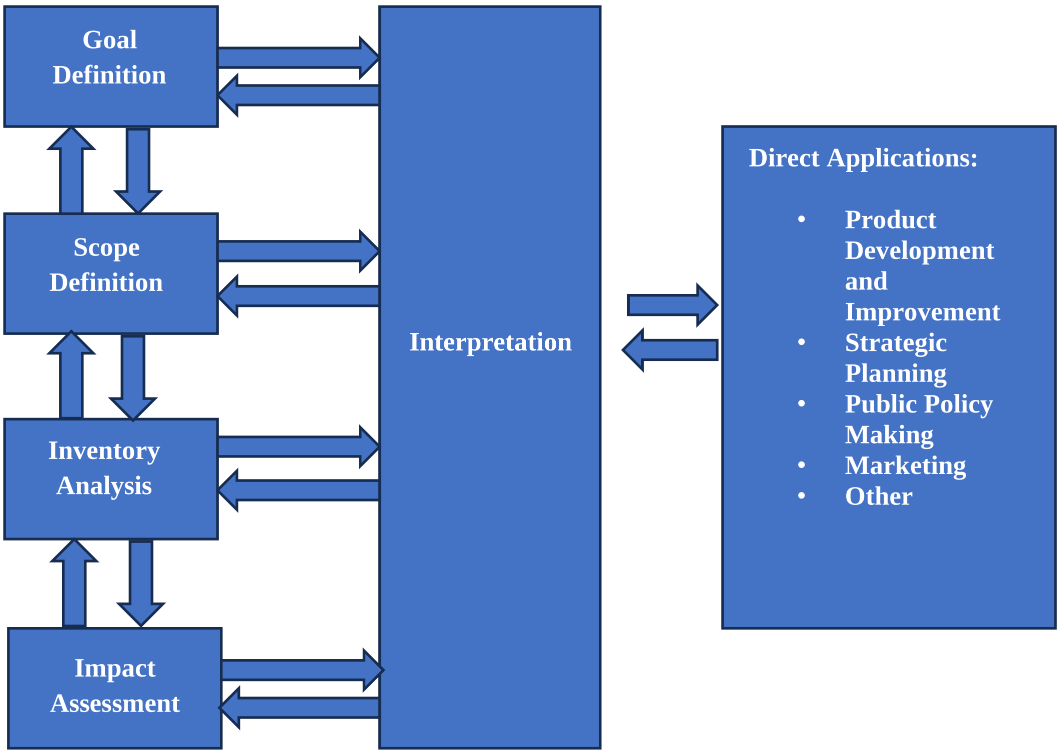

Fig. 6.9 Framework of LCA

Two different scenarios are considered in this study for life cycle assessment. Solar panel production is energy and material intensive process considering this in the first scenario, the LCA analysis has been undertaken to assess the impact of 1 tonne of solar panel production. In the second scenario two cases (case-I and case-II) are analysed, in first case, the LCA analysis has been undertaken assuming that all the material at end of life goes in a landfill. In the second case, the same processes are considered as in the first case but with the inclusion of avoided burden approach due to recycling.

Scenario I: Impact of solar PV manufacturing

Scenario II:

Case -I: Impact of disposal in Landfill

Case-II: Impact of the avoided burden approach due to recycling

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6.6.1 Defining System Boundaries

To carry out an LCA study, the goals and scope of the study must be explicitly stated. On the basis of the inventory of energy and material, the evaluation of potential environmental impacts is assessed. The Functional Unit (FU) that provides a reference to which the inputs and outputs can be related must be clearly defined. The FU in the present analysis is the treatment of 1000 kg of c-Si PV waste in a recycling facility. The system boundary of an LCA should be in accordance with the stated goal of the study and it defines the unit processes to be included in the system for analysis. Laminated Glass Recycling Facility (LGRF) processing does not require a dedicated recycling plant but recovers only aluminium, glass, and copper. This facility requires small batches of PV waste rather than a constant stream [83] while Full Recovery End-of-Life Photovoltaic (FRELP) method developed an Italian PV waste company SASIL S.p.a for recycling of PV is considered to be most advanced method. FRELP method is used in the present study and it reduces the lifetime environmental impact by 10-15% as compared to other recycling methods [91].

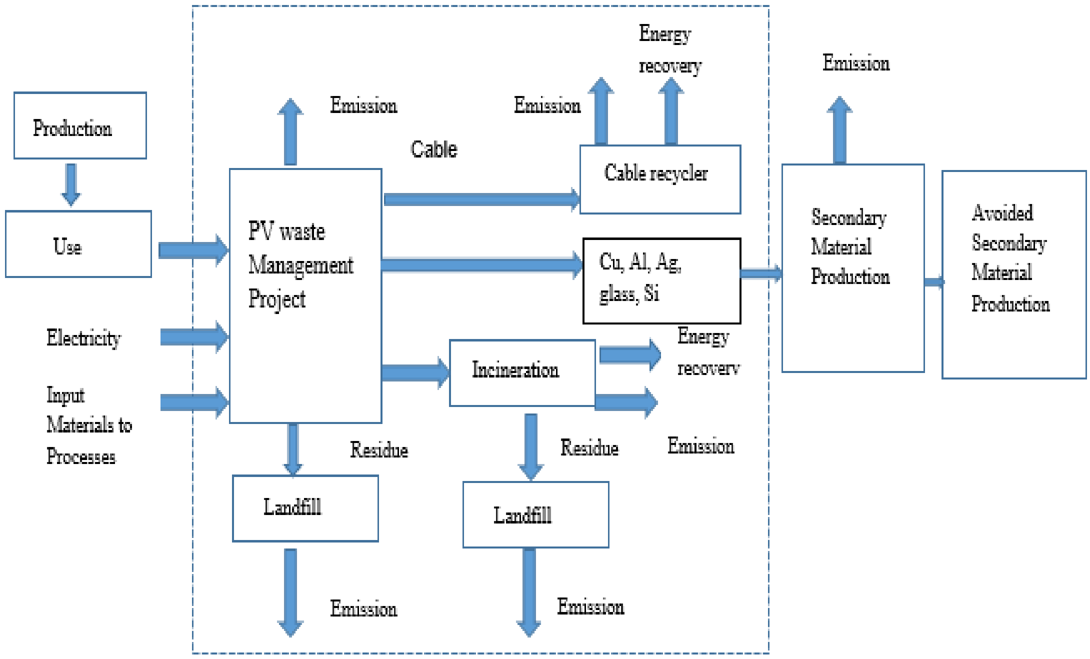

Fig. 6.10 System Boundaries for FRELP [91]

The system boundaries of the FRELP process (see Fig. 6.10) that have been taken in the present analysis exclude the processing of the aluminium, glass, copper, silver, and silicon in additional plants for the production of secondary materials [91]. The objective of this study is not only to measure the absolute values in each impact category of various disposal cases but rather to compare commonly used disposal methods to come to more definitive conclusions about how PV waste should be disposed of rationally to minimize environmental burdens

6.6.2 LCA Modelling

The LCA analysis is done using SimaPro software version 8.0 LCA software for fact-based sustainability [Online]. Available at: https://simapro.com/. The ReCiPe 2016 midpoint V1.03/World (2010) method is used to analyse environmental impacts under 18 impact categories [207]. SimaPro allows users to model and analyse complicated life cycles in a systematic, transparent manner in accordance with the recommendations of the ISO 14040 series. The input to the software is Life Cycle Inventory (LCI) data for different scenario.

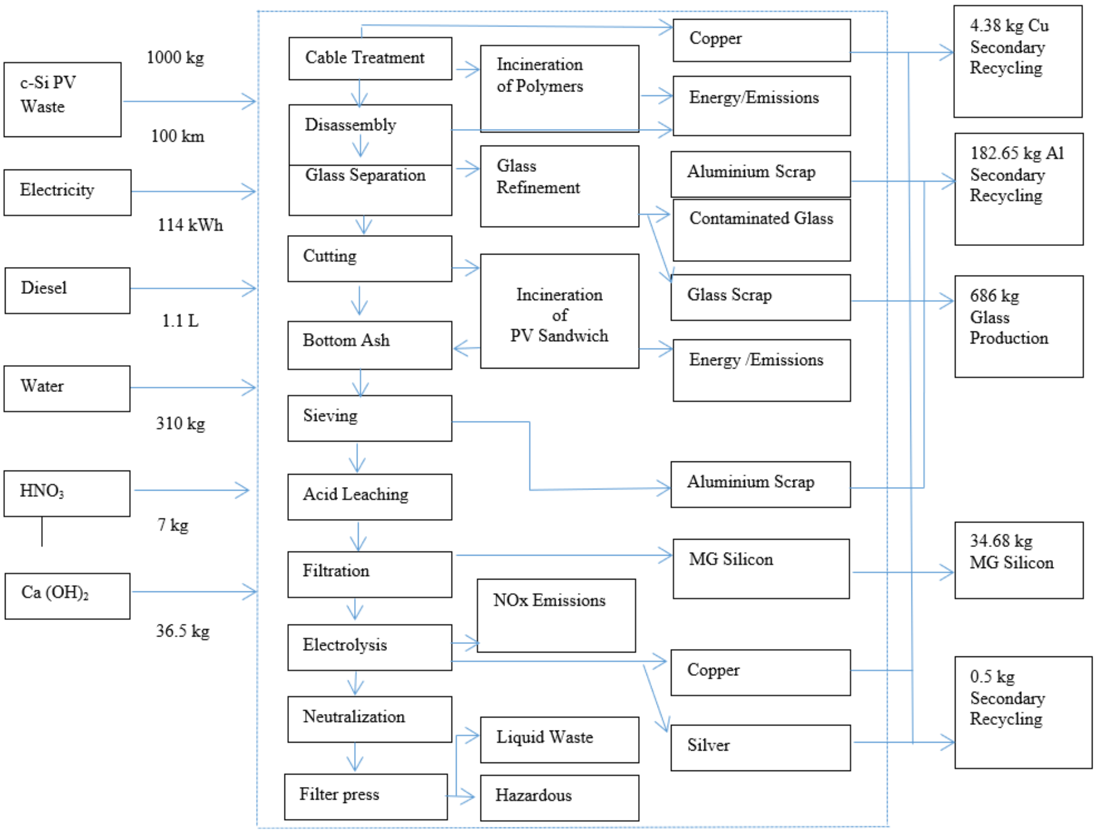

Fig. 6.11 System Diagram Showing Input and Output Stream for the FRELP Recycling Process

The present study has relied on a European data set in case of the absence of a relevant Indian dataset. The FRELP method has been utilised in the present study to carry out LCI analysis. The results and their subsequent interpretation are discussed in the following section. The list of selected background input datasets used in the LCI modelling of 1000 kg solar PV waste in the present study is given in Appendix – III (Table III.1). The laboratory tests provided by the FRELP are used to determine the composition of the PV module and the amount of materials that can be recovered are presented in Appendix IV (Table IV.1).

The system diagram for the FRELP process used by the SASIL group in Italy for recovering materials from 1000 kg of PV waste is given in Fig. 6.11 [208].The embodied energy requirement for the entire EoL treatment of c-Si PV modules is around 114 kWh/tonne of PV waste as per the FRELP process. The electrical and thermal energy quantities recovered from the incineration process of cable polymer and PV encapsulation layer are 248.84 MJ and 502.84 MJ respectively [204]. These quantities have been credited to the FU in terms of avoided impacts on the production of electricity and heat from conventional sources.

In scenario-I, the LCA analysis has been undertaken to assess the impact of 1 tonne of solar panel production (72.72 m^2). The overall results from solar manufacturing impact assessments are presented in Table 6.3. Large amounts of energy are used to convert silica sand into the high-purity silicon required for photovoltaic wafers. The purification of metallurgical-grade (MG) silicon into electronic-grade silicon during the process of producing PV cells requires 1190 MJ/panel [120]. Due to the addition of high-energy content aluminium framing and glass roofing, the PV module assembly process also consumes a lot of resources. The 18 impact categories that Recipe midpoint method models to assess the potential environmental impacts are given in Table 6.3.

For the solar PV manufacturing process, fossil fuel and energy use impacts climate change and air quality (acidification, particulate matter, etc.). Due to which a large amount of Green House Gas (GHG) and hazardous pollutants are released into the atmosphere. There is a large amount of consumption of energy and materials such as aluminium, copper, glass, etc. The process entails the extraction of raw material, manufacture, i.e., cell-matrix production, cutting of foils and washing of glass, laminate production, isolation, and the aluminium frame of the panel.

Table 6.3 Overall Impacts of the Solar Manufacturing Process (Scenario-I)

Impact Category	**Unit**	**Solar PV Manufacturing (c-Si)**
Global Warming	kg CO_2 eq	22749.859
Stratospheric Ozone Depletion	kg CFC11 eq	0.007307048
Ionizing Radiation	kBq Co-60 eq	108.91387
Ozone Formation, Human health	kg NOx eq	48.103837
Fine Particulate Matter Formation	kg PM2.5 eq	21.617138
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	50.23211

Continued on Page 90

Terrestrial Acidification	kg SO_2 eq	75.725588
Freshwater Eutrophication	kg P eq	2.036668
Marine Eutrophication	kg N eq	0.66197535
Terrestrial Ecotoxicity	kg 1,4-DCB	174726.93
Freshwater Ecotoxicity	kg 1,4-DCB	10.334238
Marine Ecotoxicity	kg 1,4-DCB	58.395577
Human Carcinogenic Toxicity	kg 1,4-DCB	2.6683154
Human Non-Carcinogenic Toxicity	kg 1,4-DCB	330.18233
Land Use	m^2a crop eq	400.1602
Mineral Resource Scarcity	kg Cu eq	88.426529
Fossil Resource Scarcity	kg oil eq	5198.4594
Water Consumption	m^3	564.27006

Since November 2022, specific regulations for solar module waste disposal were not been there, thus, the main portion of solar waste is regarded as general e-waste and dumped in an unscientific manner in landfills [191] therefore in Scenario-II, firstly, the LCA analysis has been undertaken considering that all the material at EoL goes in a landfill and impacts associated with same are studied. In case II, the avoided burden approach has been considered wherein it has been considered that solar waste materials are sent for recycling and the impact includes avoided burden due to material recycling.

The recovered materials at the EoL phase are recycled back to the manufacturing phase to gauge circular economy prospects in terms of the reduction of various environmental parameters. The potential environmental impacts associated with the production of secondary material result in avoided burden as the solar PV recycling process yields recyclable materials such as aluminium, glass, copper, and other materials, the input of virgin material into the solar PV manufacturing process can be replaced with recycled material.

6.7 Life Cycle Simulation Results Interpretation

Table 6.4 provides results of LCIA comparison for case I and case II. It can be observed that impact produced under a landfill of 1000 kg c-Si PV panels produces greater environmental impacts in all 18 impact categories as compared to the avoided burden approach due to recycling of materials using FRELP. The LCA analysis is done on SimaPro software version 8.0 [207] using the ReCiPe 2016 midpoint V1.03/World (2010) method to analyse environmental impacts under 18 impact categories. A list of background data sets given in Appendix III (Table III.1) is used to undertake the analysis.

Table 6.4 An Overall Impact Comparison of LCIA Results (Scenario-II).

Impact category	**Unit**	**Landfill (Case I)**	**Avoided Burden Approach (Recycling) (Case II)**	**% Impact Change**
Global Warming	kg CO_2 eq	73.7527	-5124.95	-22.5274
Stratospheric Ozone Depletion	kg CFC-11 eq	1.29E-05	-0.00069	-9.44294
Ionizing Radiation	kBq Co-60 eq	0.169903	-9.68052	-8.88823
Ozone Formation, Human Health	kg NOx eq	0.151898	-11.0117	-22.8915
Fine Particulate Matter Formation	kg PM2.5 eq	0.016694	-3.42764	-15.8561
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	0.155352	-11.1429	-22.1828
Terrestrial Acidification	kg SO2 eq	0.091477	-21.9033	-28.9246
Freshwater Eutrophication	kg P eq	0.000387	-0.60427	-29.6695
Marine Eutrophication	kg N eq	0.000167	-0.01886	-2.84905
Terrestrial Ecotoxicity	kg 1,4-DCB	184.0005	-6151.99	-3.52092
Freshwater Ecotoxicity	kg 1,4-DCB	0.139588	-3.33188	-32.2412
Marine Ecotoxicity	kg 1,4-DCB	0.128903	-20.8427	-35.6923
Human Carcinogenic Toxicity	kg 1,4-DCB	0.182906	-0.85843	-32.1712
Human Non-Carcinogenic Toxicity	kg 1,4-DCB	0.965908	-37.1778	-11.2598
Land Use	m^2a crop eq	2.635054	-137.462	-34.3517
Mineral Resource Scarcity	kg Cu eq	0.035884	-62.3286	-70.4863
Fossil Resource Scarcity	kg oil eq	8.492743	-978.131	-18.8158
Water Consumption	m^3	0.156098	-27.0175	-4.78804

Fig. 6.12 gives a comparative illustration of LCA results for case I and case II. The expected potential benefits of PV waste treatment are due to the avoidance of the production of primary materials due to recycling and are expressed as negative value. The major impacts associated with the case I are due to the transport and collection and treatment of waste polyethylene/polypropylene products.

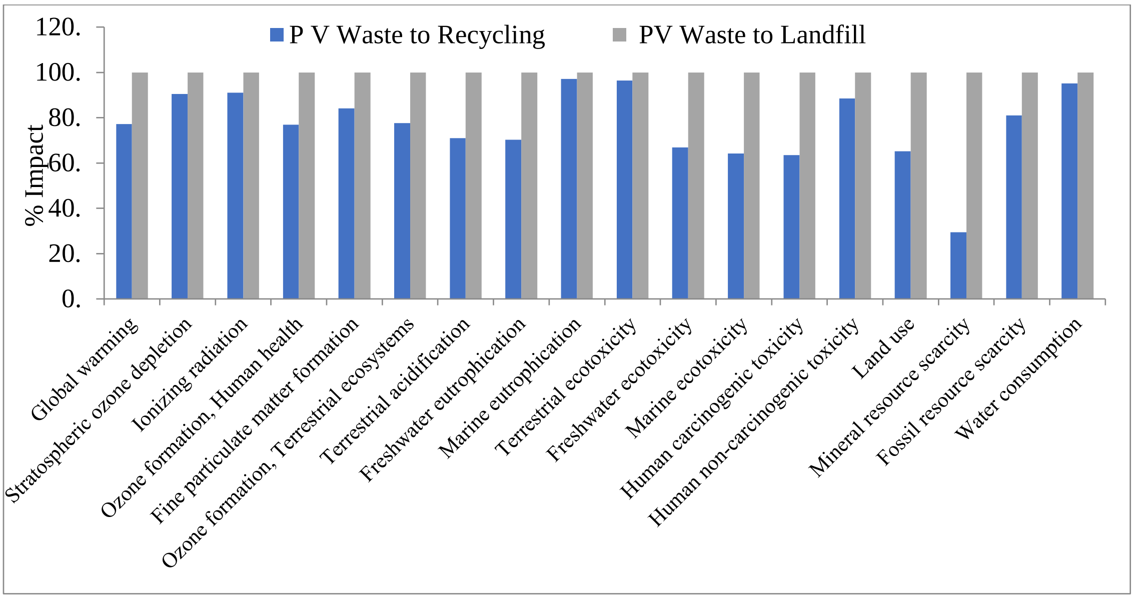

Fig. 6.12 Comparative Illustration of LCA Results

Fig. 6.13 gives a comparative percentage share due to these two parameters across all 18 impact categories and it is observed that the effect of collection, and treatment of waste polyethylene/polypropylene products under human carcinogenic toxicity is around (98%), human non-carcinogenic toxicity (76%), marine eutrophication (72%) and global warming (67%).

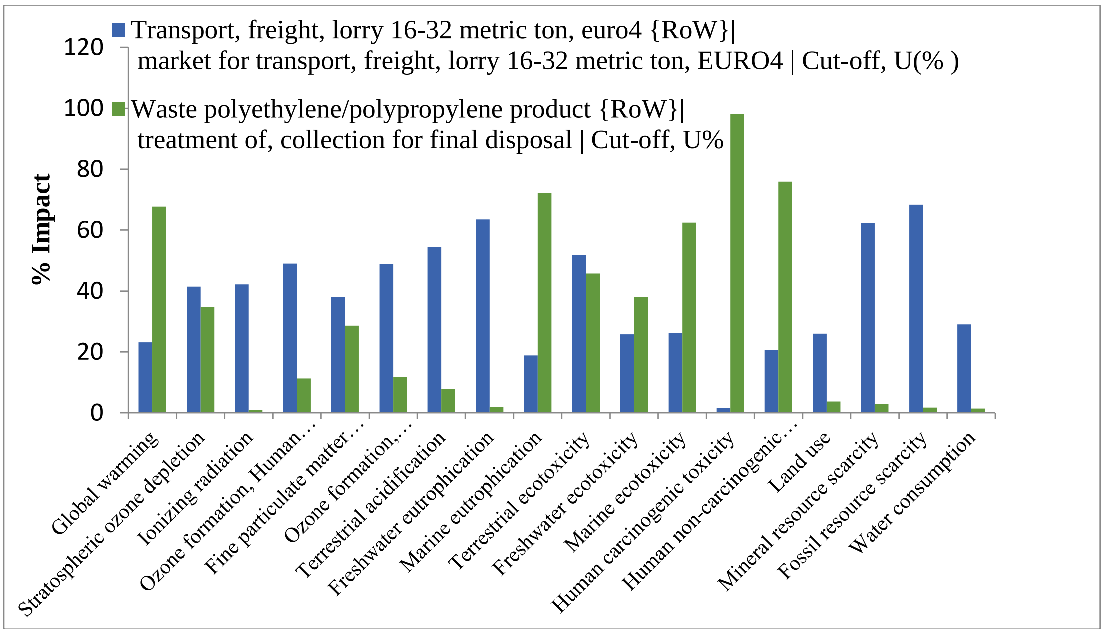

Fig. 6.13 Effect of Transport and Waste Product Treatment on Various Impact Categories

While the effect of transport is highest under fossil resource scarcity is around 68% freshwater eutrophication (64%), mineral resource scarcity (62%) and terrestrial acidification (54%). The overall environmental impacts are lower in all categories under case II on account of the obvious reason of recycling the benefit of the material as it will result in the reduction of virgin material usage. Resource extraction and material production are some of the highest impact contributors to solar PV production. Thus, recycling solar PV module components can result in avoidance of the use of virgin material for production, and lesser energy and resources for extraction and further processes will be required. A ton of aluminium (virgin metal) produced in India can have GHG emissions in the range of 16-20 TCO_2 [209], however as aluminium is recyclable, at EoL if aluminium products are recycled back into the manufacturing stream, the GHG emissions are reduced by 92% as the recycling aluminium requires 95% lesser energy than the virgin metal production [210]. Similarly, other materials such as glass, copper, silicon, silver etc. also require extensive energy, and recycling the material at the EoL back into the manufacturing and process stream can significantly reduce environmental impacts across all impact categories. Recycling of aluminium resulted in an 82% reduction in the stratospheric ozone depletion category, a 76% reduction across global warming, and an ozone formation category. Recycling glass resulted in a 44% reduction in the stratospheric ozone depletion category. Recycling silver resulted in an 88% reduction in the marine ecotoxicity category.

Nowadays, a carbon footprint, single score indicator with the application of the IPCC (Intergovernmental Panel on Climate Change) 2013, GWP model is commonly used in LCA, especially for PV panels. On the basis of IPCC 2013 GWP 100a V1.03. The comparative score for solar PV manufacturing (c-Si) is 19784.976 kg Co_2 eq and the corresponding values for landfill and avoided burden approach (recycling) are 19844.054 and 15393.96 kgCO_2 eq respectively.

6.8 Analysis and Discussions

With ambitious solar installation targets, solar waste is bound to increase in India. The PV waste if not tackled appropriately can result in a significant impact on the environment due to mishandling as well as disposal of waste in landfills. While the EU has pioneered PV electronic waste regulations including PV-specific collection, recovery and recycling other leading solar-installed capacity countries including India lack a systematic regulatory approach to handling PV waste. However, the inclusion of solar PV modules panels/ cells in the recently notified E-Waste (Management) Rules, 2022 will provide the necessary impetus for handling this problem.

The LCA analysis for different aspects relating to solar PV recycling and disposal was undertaken as part of the study to identify and highlight the most environmentally friendly solution for solar PV recycling. The LCA analysis has been undertaken considering that all the material at EoL goes in a landfill and impacts associated with same are studied in case I and in case II, the avoided burden approach has been considered wherein it has been considered that solar waste materials are sent for recycling and the impact includes avoided burden due to material recycling.

The avoided burden approach due to the recycling of materials will result in substituting virgin raw materials with recycled materials in the forthcoming production stage will result in an impact reduction for solar PV by as high as 70%. The major reduction impacts can be seen in mineral resource scarcity, marine ecotoxicity land use, freshwater ecotoxicity and human carcinogenic toxicity categories. The impact reduction results from the aspects of avoidance of primary material production due to the recycling of solar PV components at EoL. Moreover, the reuse of recovered aluminium, glass, and silver in the manufacturing phase of the PV module will not only be beneficial from an environmental impact point of view but also from an economic standpoint. The probable sources of some of the uncertainties in the present study that may affect outcomes of solar waste estimation and its effect on the environment are also discussed. This study aims to apprise researchers, policymakers, and other stakeholders of impending problems that may arise due to EoL solar PV e-waste in India. The country is facing significant challenges in attaining the dual goals of energy security and sustainability due to inadequate infrastructure, waste management practices, and recycling regulations.

The present study recommends the following strategies to handle the ever-growing solar waste problem in India:

i. The establishment of an online monitoring system to track the flow of all discarded modules at all stages of the PV life cycle will provide input for authorities and other stakeholders to develop regulations and policies.

ii. Imparting skills in PV panel repairs will enable the development of the second-hand market of solar PV modules wherein modules can be sold and purchased after doing necessary minor repairs.

iii. In the long term, extensive R&D will limit waste production & the establishment of pilot recycling plants to recover the secondary materials. However, the viability of waste recovery models cannot be guaranteed owing to low to moderate values of PV waste generation. The government may therefore consider incentivizing the waste recovery units for a few initial years.

iv. A multi-sector and multi-stakeholder coordinated approach among various stakeholders including ministries and manufacturers along with EPR legislation that will cover the provision of collection, recovery, and recycling of solar PV.

6.9 Concluding Remarks

In the present chapter, the waste projection results as per the BAU scenario are estimated. The results shows that the PV waste could reach up to 5.7 million tonnes due to the early loss scenario and 4.24 million tonnes due to the regular loss scenario while in the ambitious scenario, the waste estimation is 7.36 million tonnes due to the early loss scenario and 5.96 million tonnes due to the regular loss scenario by the end of 2040 in India. These results of the present study vary from the results of earlier studies, mainly on account of COVID-19 pandemic disruptions, variation of t/MW factor, and the lifetime of solar panels.

The analysis of two scenarios for life cycle assessment is considered in present study. In the first scenario impact of solar PV manufacturing is analysed. While in second scenario, a comparison between case of waste material at end-of-life cycle going to landfill is compared to case of avoided burden approach due to recycling. The avoided burden approach due to the recycling of materials results in substituting virgin raw materials with recycled materials in the forthcoming production stage and therefore results in reduced environmental burdens in all categories.

Further, results of carbon footprint, single score indicator with the application of the IPCC (Intergovernmental Panel on Climate Change) 2013, GWP model also indicate comparative lower values for avoided burden approach due to recycling in comparison to landfill option.

CHAPTER 7

CONCLUSION, SOCIAL IMPACT OF RESEARCH AND FURTHER SCOPE OF WORK

7.1 Introduction

The expansion of solar PV energy is pivotal for India's economic growth, environmental protection, energy security and shaping sustainable future, it also presents challenges that need to be addressed through policy interventions, technological innovation, and community engagement.

The main objective of this research work is to delve deep into the challenges plaguing the solar industry, including the rationalization of incentives, management of diurnal variability through battery storage, addressing soiling issues, and handling solar waste, while proposing effective solutions for each of these areas. Despite of considerable growth of solar PV in the last decade, the country is still facing several impediments that have affected the growth and, in all likelihood, will impose a serious challenge in years to come. In order to strike a balance between the profitability of investors and consumers' interest it is necessary that nuances of solar tariff determination be understood in the first place. The techno economics of battery energy storage solution for a grid-connected plant has been conducted using GAMS. The operational issue of soiling has been dealt with through experiment on the outdoor test bed. The thesis also highlights the need to focus on the impending problem of solar waste disposal to prevent waste from reaching landfills and presents an environmentally benign strategy to policymakers for the handling of solar waste using LCA methodology. The present chapter provides the main conclusions of the study as well as a discussion on the social impact of research and the future potential of the study.

7.2 Main Conclusions

The following are the main key conclusions of the research study that is being presented in a chapter wise manner:

i. The role of various direct incentive schemes in achieving a desired value of LCOE for solar PV plants have been compared in **Chapter 3** and it has been observed from the cost-effectiveness index matrix that GBI is scoring high among VGF, GBI, and AD. The research highlights that while initial government subsidies like VGF, AD, and GBI were crucial during solar energy's early growth cycle in India, the focus is now shifting as LCOE are coming down. Although direct incentives may be pulled back, continued support through mechanisms like transmission charge waivers and import duty exemptions remains essential for the sustained competitiveness and viability of solar PV projects.

ii. **Chapter 4** presents that through system modelling using GAMS, the ToD regime offers more saving opportunities in comparison to the flat tariff rate regime and the sizing of the battery is a function of the ToD tariff and input cost of power. The integration of distributed energy sources like PV and BESS enhances the reliability, and economic viability of the energy system.

iii. In **Chapter 5,** it has been demonstrated experimentally that during study period between November 2022-August 2023, the soiling rates during were higher in winter than in summer and rainy seasons. The losses are found to be highest in January 2023 and lowest in July 2023. The average soiling loss per month during the study period was 7.6% that amounts to the daily soiling loss of 0.25%. The results indicate that the improvement of air quality and periodic cleaning of solar panels will improve the utilization of solar energy in Delhi.

iv. The study undertaken in **Chapter 6** estimates the volume of solar PV waste in India using the Weibull function and also presents an environmentally benign strategy to policymakers for the handling of solar waste using LCA methodology carried through SimaPro software. The waste projection results as per the BAU scenario estimated that the PV waste could reach up to 5.7 million tonnes due to the early loss scenario and 4.24 million tonnes due to the regular loss scenario while in the ambitious scenario, the waste estimation is 7.36 million tonnes due to the early loss scenario and 5.96 million tonnes due to the regular loss scenario by the end of 2040 in India. It has been demonstrated through LCA that the avoided burden approach due to the recycling of materials will result in substituting virgin raw materials with recycled materials in the forthcoming production stage and will result in an impact reduction for solar PV by as high as 70%.

7.3 Social Impact of Research

The lives of millions of people in India have benefited from decentralized and distributed solar energy applications like lighting, cooking, pumping etc. The present thesis has identified the research objectives taking into account the widespread development of solar throughout the country. The societal benefits attributable to research objectives can be categorized as:

i. Economic and Policy Impacts

- **Cost Reduction and Affordability:** The reduction in the Levelized Cost of Energy (LCOE) for solar PV projects due to government subsidies and market dynamics has made solar energy more affordable for consumers. This can lead to lower energy bills and increased access to renewable energy, potentially enhancing quality of life and economic stability for households and businesses.

- **Enhanced Investment and Job Creation:** As the industry is maturing and moving to auction-based pricing, it has created a competitive market environment. This has resulted in more investment and improved efficiency. The growth of the solar industry has created numerous job opportunities in manufacturing, installation, maintenance, and research. This has resulted in overall economic development and skill enhancement in various regions, particularly in rural and underdeveloped areas.
- **Policy Development**: Understanding the nuances of various incentive schemes helps in rationalizing policies to support the solar industry. By analysing the effectiveness of these incentives, the study assists policymakers in formulating strategies that boost industry growth without imposing undue financial burdens on consumers. This can lead to better investment conditions and more stable energy prices.

ii. Environmental Impacts

- **Waste Management Challenges:** The anticipated increase in solar PV waste due to defective and end-of-life panels poses significant environmental challenges. Without proper regulations and infrastructure for waste management, there is a risk of waste being inappropriately incinerated or landfilled. Further, toxic materials in solar panels like cadmium, lead etc might pose a health risk if solar waste is not handled properly. By developing efficient recycling and disposal techniques, the threats to society may be reduced
- **Pollution and Cleaning Costs Concerns:** The accumulation of dust and dirt on PV panels, particularly in polluted areas like Delhi, affects performance and increases maintenance costs. This leads to additional financial burden due to the requirement of frequent cleaning, which has environmental implications. Addressing soiling losses effectively can reduce operational costs and improve the overall efficiency of solar energy systems and enable wider deployment by society.

iii. Technological and Deployment Impacts

- **Enhanced BESS deployment:** The study's focus on Battery Energy Storage Systems (BESS) in Delhi, with its unique load patterns and extreme weather conditions, highlights the importance of integrating storage solutions to manage energy demand efficiently. The success of such deployment will encourage more buildings to adopt similar technologies, ultimately leading to less dependence on fossil-based generation sources.
- **Energy Access and Equity:** Increased adoption of solar energy will ensure energy access in remote and underprivileged locations, potentially mitigating disparities in energy availability. This will enhance the quality of life and socioeconomic growth of society at large.

7.4 Suggestions for Future Work

For further development of the work undertaken in the present thesis, the following recommendations are presented below:

i. Various incentives and schemes are currently being run by MNRE for grid-connected rooftop PV systems, solar water pumping systems, solar parks etc. A similar analysis as conducted in Chapter 3 can be conducted on the economics of these systems as a part of future work. Given the quest for a sustainable 24 X 7 supply solution for a country like India, the effect of energy storage on the levelized cost of energy for photovoltaic systems is also a topic of considerable importance for future research.

ii. The study undertaken in Chapter 4 for the Delhi Secretariat building can be broadened to achieve the net zero energy building target for the same building for future research. The capacity of installed solar PV systems and battery storage capacity is required to be enhanced to achieve this objective.

iii. The impact of natural wind and tilt angle optimization on soiling losses could be included to improve the analysis done in the study presented in Chapter 5. This study can be further extended by considering the role of the self-cleaning capability of panels against soiling.

iv. The absence of availability of accurate data like life span, shape and scale parameters etc. relating to BOS is the main hindrance behind their inclusion in the analysis presented in Chapter 6. As a potential avenue of future research, the analysis carried out in the present study can be further enhanced by the inclusion of BOS along with PV modules. Another opportunity for future research lies in carrying out sensitivity and cost-benefit analysis of the recycling process.

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Appendix-I

Table I.1 Project Summary Sheet

Project Capacity (MW)	1
Life of Project (Years)	25
Capacity Utilisation Factor of the Project (%)	19
Annual Energy Production (Lakh kWh)	16.644
Total Project Cost (Rs. Lakh)	530.02
Equity to be Invested (Rs. Lakh)	159
Loan Component (Rs. Lakh)	371
Loan Repayment Period (Years)	12
Return on Equity for 1-10 Years (P.A.)	0.2
Return on Equity for 11-25 Years (P.A.)	0.24
Depreciation Till Loan Repayment (%)	0.0583
Depreciation After Loan Repayment (%)	0.0154
Total O&M Expenses for 1st Year (Rs. Lakh)	7
Escalation in O&M Expenses (%)	0.0572
Discount Rate (%)	0.1064

Appendix-II

Table II.1 Tariff Calculation Summary Sheet

Tariff Calculations \ Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Energy Sold	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6
O&M Expenses	7.0	7.4	7.8	8.3	8.7	9.2	9.8	10.3	10.9	11.5	12.2	12.9	13.6	14.4	15.3	16.1	17.0	18.0	19.1	20.1	21.3	22.5	23.8	25.2	26.6
Depriciation	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Interest on Term Loan	45.53	41.6	37.6	33.7	29.8	25.8	21.9	17.9	14.0	10.0	6.1	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Interest on Working Capital	2.82	2.62	2.55	2.47	2.40	2.33	2.26	2.19	2.12	2.05	2.13	2.07	1.53	1.56	1.59	1.62	1.65	1.69	1.73	1.76	1.80	1.85	1.89	1.94	1.99
Return on Equity	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2	38.2
Total Fixed Cost	118.1	114.3	110.7	107.1	103.6	100.1	96.6	93.1	89.7	86.3	89.5	86.2	61.5	62.3	63.2	64.1	65.0	66.0	67.1	68.2	69.4	70.7	72.0	73.4	74.9
Cost per Unit of Electricity	7.09	6.87	6.65	6.44	6.22	6.01	5.80	5.60	5.39	5.19	5.38	5.18	3.70	3.74	3.80	3.85	3.91	3.97	4.03	4.10	4.17	4.25	4.33	4.41	4.50
Tariff with VGF	7.1	6.5	6.3	6.1	5.9	5.7	5.5	5.3	5.1	4.9	5.0	4.8	3.6	3.7	3.7	3.8	3.8	3.9	3.9	4.0	4.1	4.2	4.2	4.3	4.4
Tariff with GBI	5.29	5.07	4.85	4.63	4.42	4.21	4.00	3.79	5.39	5.19	5.38	5.18	3.70	3.74	3.80	3.85	3.91	3.97	4.03	4.10	4.17	4.25	4.33	4.41	4.50
Discount Rate for Net present Value	0.1																								
Discount Factor	1.00	0.90	0.82	0.74	0.67	0.60	0.55	0.49	0.45	0.40	0.36	0.33	0.30	0.27	0.24	0.22	0.20	0.18	0.16	0.15	0.13	0.12	0.11	0.10	0.09

Table II.2 Summary of Results After Consideration of Various Incentive Schemes

Levelized Tariff (Rs./kWh)	Levelized Tariff with VGF (Rs./kWh)	Levelized Tariff with GBI - 2 year (Rs./kWh)	Levelized Tariff with GBI -8 year (Rs./kWh)	Levelized Tariff with AD (Rs./kWh)
5.68	5.43	5.32	4.59	5.14

Appendix-III

Table III.1 List of Background Input Datasets Used in the Life Cycle Inventory Modelling

Item	Used for the process phase	Datasets
Electricity	Solar Panel Disassembly, Electrical Cable Treatment, Separation of Glass and Refinement, PV Sandwich Layer Cutting, Sieving, Acid Leaching, Filtration, Electrolysis, Neutralisation And Filter Press	Electricity, High Voltage {IN-Western Grid}| Market for Electricity, High Voltage
Thermal energy	Heat	Heat, Central or Small-Scale, Other Than Natural Gas {Row}| Heat Production, Light Fuel Oil, at Boiler 10kw, Non-Modulating
Transport	PV Waste Transportation to the Recycling Plant	Transport, Freight, Lorry 16-32 Metric Ton, Euro4 {Row}| Market for Transport, Freight, Lorry 16-32 Metric Ton, EURO4
	PV Waste Transportation to Local Collection Point; Cables Transportation to Cable Treatment Plant and Cable Polymer Transportation to the Incineration Plant; Transport of Glass Residue to Landfill; PV Sandwich Transportation to Incinerator; Transport of Ash to the Treatment Plant; Transportation of Fly Ash to Special Landfill	Transport, Freight, Lorry 16-32 Metric Ton, Euro4 {Row}| Market for Transport, Freight, Lorry 16-32 Metric Ton, EURO4
	Sludge transportation from the recycling plant to landfills	Transport, freight, lorry 16-32 metric ton, euro4 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO4

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Item	Used for the process phase	Datasets
Landfilling of the Contaminated Glass	Glass Refinement	Waste Glass {GLO}| Waste Glass Treatment, Unsanitary Landfill, Moist Infiltration Class
Disposal of Fly Ash in a Landfill	Incineration	Fly Ash and Scrubber Sludge {Row}| Treatment of, Hazardous Waste Incineration
Water	Acid Leaching, Electrolysis, Neutralisation	Water, Unspecified Natural Origin, IN
Nitric Acid	Acid Leaching	Nitric Acid, Without Water, in 50% Solution State {Row}| Market for Nitric Acid, Without Water, in 50% Solution State
$Ca(OH)_2$	Neutralisation	Lime, Hydrated, Loose Weight {Row}| Market for Lime, Hydrated, Loose Weight
Limestone Residue	Landfill	Limestone Residue {Row}| Treatment of, Inert Material Landfill
Landfilling Of Sludge with Metal Residuals	Filter Press	Sludge, Pig Iron Production {CH}| Treatment of, Residual Material Landfill

Appendix-IV

Table IV.1 Amount of Recovered Materials Based on Mass Composition in BAU and Ambitious Scenario (C. E. L. Latunussa et al. 2016a, pp. 101-111)

	Mass Composition of 1 Ton of Crystalline-Silicon PV Waste as Input to the Recycling Process		Mass Composition of PV Waste as Input to the Recycling Process				Mass Composition of PV Waste as Input to the Recycling Process			
			BAU Scenario				Ambitious Scenario			
			2030 (t/MW = 50.72)		2040 (t/MW = 38.72)		2030 (t/MW = 50.72)		2040 (t/MW = 38.72)	
Component	**Quantity**	**Percentage**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**
	(kg)	**(%)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**
Glass, Containing Antimony (0.01-1%/Kg of Glass)	700	70%	717317	1883976	3838327	4645641	791636	2079169	5955818	7208502
PV Frame, Made of Aluminium	180	18%	184453	484451	986998	1194593	203564	534643	1531496	1853615
Polymer-Based Adhesive (EVA) Encapsulation Layer	51	5.1%	52262	137261	279650	338468	57676	151482	433924	525191
Solar Cell, Containing Silicon Metal	36.5	3.65%	37403	98236	200141	242237	41278	108414	310553	375872
Back-Sheet Layer (Based on Polyvinyl Fluoride)	15	1.5%	15371	40371	82250	99549	16964	44554	127625	154468
Cables (Containing Copper and Polymers)	10	1%	10247	26914	54833	66366	11309	29702	85083	102979

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	Mass Composition of 1 Ton of Crystalline-Silicon PV Waste as Input to the Recycling Process		Mass Composition of PV Waste as Input to the Recycling Process				Mass Composition of PV Waste as Input to the Recycling Process			
			BAU Scenario				**Ambitious Scenario**			
			2030 (t/MW = 50.72)		**2040 (t/MW = 38.72)**		**2030 (t/MW = 50.72)**		**2040 (t/MW = 38.72)**	
Component	**Quantity**	**Percentage**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**	**Regular-Loss Scenario Quantity**	**Early-Loss Scenario Quantity**
	(kg)	**(%)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**	**(t)**
Internal Conductor, Aluminium	5.3	0.53%	5431	14264	29062	35174	5994	15742	45094	54579
Internal conductor, copper	1.14	0.114%	1168	3068	6251	7566	1289	3386	9699	11740
Silver	0.53	0.053%	543	1426	2906	3517	599	1574	4509	5458
Other metals (tin, lead)	0.53	0.053%	543	1426	2906	3517	599	1574	4509	5458
Total	**1000**	**100%**	**1024739**	**2691395**	**5483325**	**6636630**	**1130909**	**2970241**	**8508311**	**10297859**

CURRICULUM VITAE

ABHISHEK SHARMA
Flat No 19, Plot No. 99
Ras Vihar Appartement
I. P. Extension, Delhi
Mobile : 09999533870
E-mail : abhishek.sharma39@gov.in, abhiabhi30@gmail.com

PROFESSIONAL EXPERIENCE

Jan 2024- till date — **Director in Bureau of Energy Efficiency, Ministry of Power, Government of India**

The Role:

- State Related Activities and Financial Matters of States
- Standard and Labelling of appliances (star rating)
- Check testing of appliance

Nov 2018- Dec 2023 — **Joint Director in Bureau of Energy Efficiency, Ministry of Power, Government of India**

The Role:

- State Related Activities and Financial Matters of States
- Net Zero Energy Building
- Agriculture and Municipal Demand side Management

Since November 2017 - November 2018 — **Manager in Energy Efficiency and Renewable Energy Management Centre (EE&REM), State Designated Authority (SDA), Delhi.**

The Role:

- Energy Efficiency and conservation related activities for Delhi
- Organizing Workshop seminars, awareness Programme

Since December 2015 - November 2017 — **Assistant Manager in Energy Efficiency and Renewable Energy Management Centre (EE&REM),**

State Designated Authority (SDA), Delhi.

The Role:

- Energy efficiency and Energy conservation
- RPO compliance and Energy Audit

Since November 2006 -December 2015 **Assistant Manager (Technical) in Delhi Transco Limited (State Transmission Utility).**

The Role:

- Worked as overall in charge of 220 KV substation Pragati, located in the heart of Delhi.
- In training department to impart relevant training through external or internal training programme to each & every employee of the organization.
- Worked as Technical Officer for Perform Achieve and Trade (PAT) related activities for Delhi.

Since January 2006 -October 2006 **Management Trainee in Steel Authority of India Limited at Bhilai Steel Plant**

The Role:

- As a trainee learned the importance of coordination between various Centres/Activities in an integrated steel plant that takes place to produce the final output i.e Steel.

Since September 2002 - December 2006 **Telecom Technical Assistant in Bharat Sanchar Nigam Limited at Faridabad**

The Role:

- Worked in Team responsible for Installation of Telephone Exchange in various Location of Faridabad

.

EDUCATIONAL CREDENTIALS

Professional Qualification

Pursuing PhD from Delhi Technology University (DTU)

July, 2012	Master of Technology in Energy & Environment Management from Indian Institute of Technology Delhi with CGPA 8.95/10.
October, 2002	Bachelor of Technology in Electrical Engineering from Delhi College of Engineering, Delhi with overall percentage of 82.93%.

PG Diploma

May, 2014	PG Diploma in Urban Environment Management & Law from WWF-INDIA

Certifications

July, 2010	Bureau of Energy Efficiency, India certified Energy Manager & Energy Auditor.
June, 2012	IRCA Certified ISO 9001:2008 Quality Management Systems Lead Auditor

PERSONAL DETAILS

Date of Birth	:	30th August 1979
Marital Status	:	Married

(ABHISHEK SHARMA)