PHOTOVOLTAIC POWER PLANT INSTALLATION VARIANTS AND THEIR STRATEGIC ADOPTION IN INDIA'S ELECTRICITY SECTOR FOR CREATING SUSTAINABLE COMMUNITIES

by

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DEDICATION

This dissertation is dedicated to the pursuit of excellence in achieving the Doctorate in Business Administration (DBA). With deep love and gratitude, I dedicate this work to my family, whose blessings and legacy continue to inspire me.

ABSTRACT

PHOTOVOLTAIC POWER PLANT INSTALLATION VARIANTS AND THEIR STRATEGIC ADOPTION IN INDIA'S ELECTRICITY SECTOR FOR CREATING SUSTAINABLE COMMUNITIES

Prashant Kumar Bairagi

2025

The transition to renewable energy is a cornerstone of global efforts to combat climate change and promote sustainable development. This thesis investigates the strategic adoption of photovoltaic (PV) power plant installation variants within India's electricity sector to foster sustainable communities. Recognizing India's significant solar energy potential and its unique socio-economic and infrastructural challenges, the research employs a comparative analysis of various PV installation types, including rooftop solar, ground-mounted plants, and emerging technologies like floating solar. Through case studies, stakeholder interviews, and secondary data, the study evaluates the efficiency, cost-effectiveness, and environmental impact of these systems across diverse Indian contexts. The findings reveal that strategic PV deployment can significantly reduce energy costs, enhance energy security, mitigate carbon emissions, and stimulate economic growth, particularly in underserved regions. However, challenges such as high initial capital costs, regulatory hurdles, and uneven policy implementation are also highlighted. To address these issues, the thesis proposes a multi-stakeholder framework integrating financial innovations, tailored policy interventions, and community-centric approaches to maximize the socio-economic and environmental benefits of solar energy adoption. This research contributes actionable insights for policymakers, energy practitioners, and community leaders aiming to leverage solar energy to achieve India's renewable energy targets and the UN Sustainable Development Goals (SDGs).

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A special acknowledgment goes to my company "Stride Climate Investments" and my wonderful teammates. Their guidance, collaboration, and support have been invaluable in shaping this accomplishment.

Finally, I am profoundly thankful to my wife and kids. Their support during the research journey will always be remembered with gratitude.

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CHAPTER 1

INTRODUCTION

India's power sector is fundamental to the country's economic development and social progress, serving as the backbone for industries, agriculture, and domestic energy needs. As the third-largest producer and consumer of electricity globally, India has made significant strides in expanding its energy infrastructure to meet the demands of a rapidly growing population and an ever-expanding economy. The sector's ability to adapt and evolve has been instrumental in addressing challenges related to energy access and security, while also supporting the nation's ambitious development goals.

If we closely look at the India's electricity infrastricture, it is primarily dominated by coal power plants, which have historically formed the backbone of the country's energy sector. Despite the increasing environmental concerns surrounding coal-fired power plants, their reliability and cost-effectiveness continue to make them a significant component of the energy mix. However, recognizing the environmental and efficiency-related limitations of older coal power plants, India has begun retiring outdated facilities, with approximately 20,086.88 MW of coal-based capacity planned for decommissioning (see *Figure 1.1.(a)*). This move reflects the country's commitment to modernizing its energy infrastructure and reducing its carbon footprint while maintaining energy security. As of 2025-26, India's operational electricity generation capacity has reached a staggering 490,050.69 MW, underscoring the government's efforts to ensure adequate energy supply for its population of over 1.4

billion people. To further bolster its capacity and meet future demand, India has an additional 195,073.54 MW of new power projects in the pipeline, which are expected to commence operations in the near term (see *Figure 1.1.(b) and 1.1.(c)*). These projects are a mix of conventional and renewable energy sources, highlighting the country's dual approach of leveraging existing resources while gradually transitioning to low-carbon alternatives.

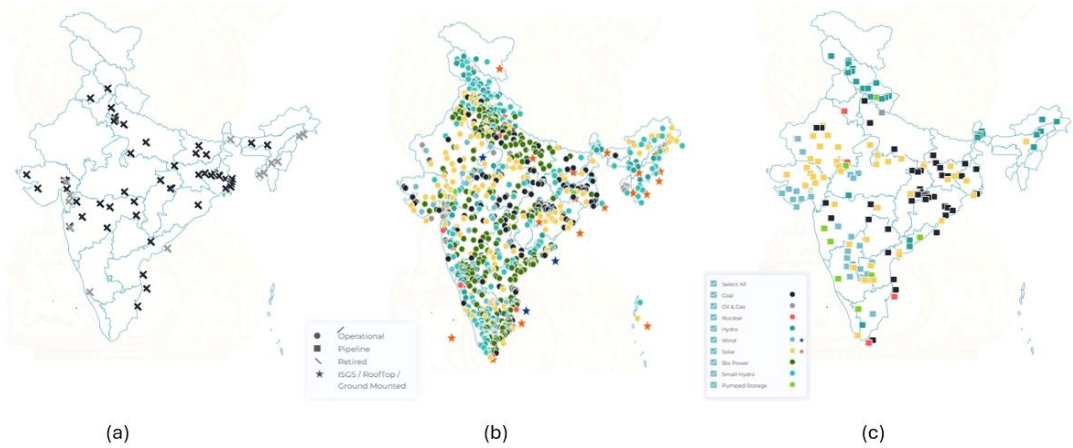


Figure 1.1. *India's power map (mix of fossil fuel, renewables, and nuclear energy) accounting for retired, operationaly and projects under pipeline across states and union territories. (a). Retired power capacity in MW; (b). Operational Power Capacity in MW; and (c). Projects under pipeline in MW.*

While coal remains a dominant energy source, India's power sector has witnessed a remarkable shift toward renewable energy in recent years. Solar, wind, hydro, and bio-power are now essential components of the energy mix, driven by the government's ambitious renewable energy targets. The country's installed solar capacity, for instance, has grown exponentially, reflecting its critical role in reducing dependency on fossil fuels and achieving sustainability goals. These advancements are part of India's broader strategy to meet its international climate commitments, including its pledge to achieve 500 GW of non-fossil fuel capacity by 2030 under the Paris Agreement. India's pledge to achieve 500 GW of non-fossil fuel capacity by 2030 was announced by Prime Minister Narendra Modi at the COP26 summit in Glasgow in 2021 as part of its updated Nationally Determined Contributions (NDCs) for the Paris Agreement. This ambitious goal includes large hydropower and nuclear power in addition to renewables like solar and wind, and it aims to ensure non-fossil fuel sources account for roughly 50% of the nation's total installed power capacity by the end of the decade.

Figure 1.2. *National level electricity installaed capacities and generation trends in India from 2015 to 31st July 2025. (Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited)*

After analyzing the national-level electricity installed capacities and generation trends in India from 2015 to 31st July 2025 (*see Figure 1.2*), it is evident that the country has made significant progress in expanding its energy infrastructure and meeting the growing energy demands of its population as well as the ambitous pledge to achieve 500 GW of non-fossil fuel capacity by 2030 under the Paris Agreement. Over the last decade, India has demonstrated its commitment to addressing energy security and fostering economic growth through a mix of conventional and renewable energy sources. The increase in installed capacity and generation reflects the efforts of policymakers, industry stakeholders, and the government in ensuring reliable and consistent electricity supply across the country. Despite its achievements, India's power sector faces several challenges. High transmission and distribution losses, financial stress on distribution companies (DISCOMs), and the need for investments in energy storage and grid modernization are pressing issues that require attention. Additionally, the retirement of coal plants presents challenges in ensuring grid stability and maintaining a reliable supply during the transition to renewables. However, these challenges also offer opportunities for innovation, economic growth, and technological advancements in clean energy technologies. To name these opportunities, the transition to renewable energy has introduced innovation and growth in the energy sector decentralization and application specific point of use energy production, particularly with the rapid adoption of solar, wind, biomass, and other clean energy technologies.

1.1. Deep-dive into India's Installed Energy Capacities and Generation

India's power sector is an intricate and dynamic system, structured around three major segments: generation, transmission, and distribution. Among these, generation plays the most critical role in supplying electricity to meet the demands of the population and industries. The generation segment is further categorized into thermal power (coal, gas, and oil), renewable energy (solar, wind, hydro, and biomass), and nuclear energy, each contributing differently to India's energy mix. Historically, coal has been the dominant energy source, powering the country's rapid industrial growth and urbanization. According to the Central Electricity Authority (CEA, 2021), coal accounted for nearly 70% of electricity generation, reflecting its essential role in ensuring energy security. However, this dominance comes with significant environmental costs, including carbon emissions and air pollution, prompting a shift toward renewable and cleaner energy sources.

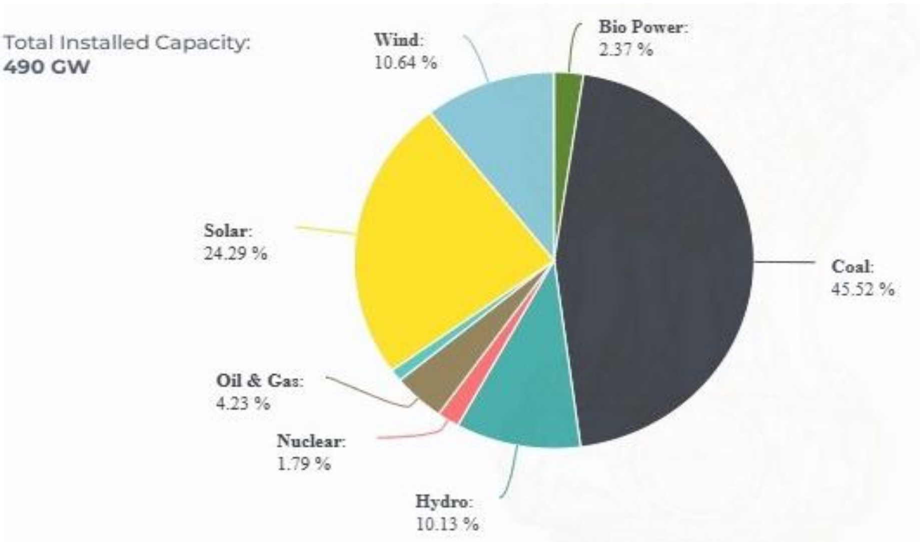


Figure 1.3. *Source-wise electricity installed capacities in India along with % of share in 490 GW. (as on 31st July 2025, Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited)*

India's power sector is currently undergoing a structural transition. The total installed capacity is projected to reach 490 GW by 2025-26, with renewable energy taking a growing share of this capacity (see *Figure 1.3.*). This shift toward renewables is mirrored in electricity generation trends, where the contribution of renewable sources has been steadily increasing. At the same time, coal's dominance in power generation is gradually declining as India moves toward a more diversified energy mix. This transition is driven by a combination of ambitious government policies, global climate commitments, and advancements in clean energy technologies. Year-on-year (YoY) growth rates in electricity generation reflect this progress, particularly in renewable energy adoption. The YoY growth rate peaked at 8% in 2021-22, marking the sector's recovery from the COVID-19 pandemic-induced slowdown and showcasing the rapid expansion of renewable energy technologies (*see Figure 1.4*).

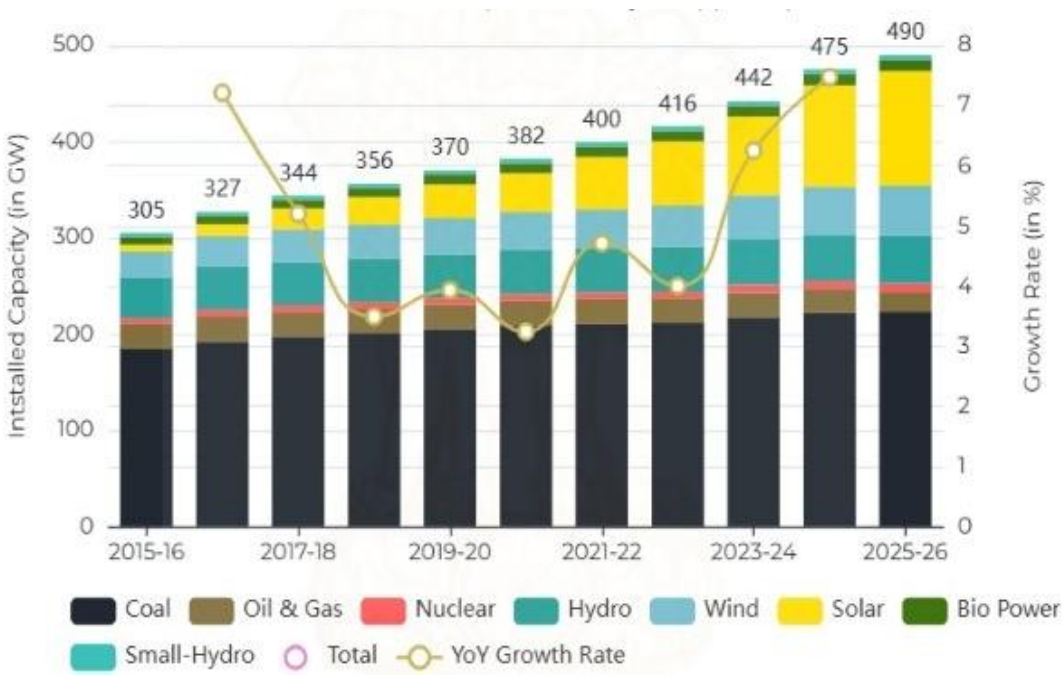


Figure 1.4. *Source-wise electricity installed capacities trends in India in GW along with year on year growth rate for the years from 2015 to 2026. (as on 31st July 2025, Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited)*

Despite the growth of renewables, coal continues to dominate India's energy generation, accounting for 68.66% of electricity production in 2025-26, as per projections (*see Figure 1.5.*). This reliance underscores the critical role coal plays in powering India's economy, particularly in meeting the base-load electricity demand. However, the share of coal in India's total installed capacity is projected to decline to 45.52% by 2025-26 (*see Figure 1.6.*). This reduction reflects the gradual decommissioning of older, less efficient coal plants and the increasing adoption of cleaner technologies. While coal remains indispensable for now, the long-term outlook indicates a shift toward reducing its share in favor of renewable energy.

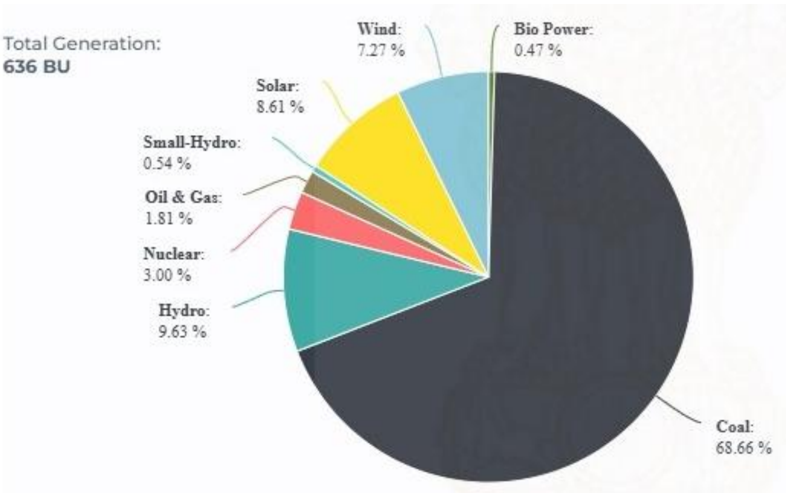


Figure 1.5. *Source-wise electricity generation in India along with % of share in 636 BU for the year 2025-26. (as on 31st July 2025, Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited)*

Other conventional energy sources, such as oil and gas, contribute only a small portion to India's energy generation. By 2025-26, oil and gas are expected to account for 1.81% of electricity production and 4.23% of installed capacity (*see Figures 1.3. and 1.5.*). The limited role of oil and gas highlights their declining competitiveness, especially when compared to the cost-effectiveness and sustainability of renewable alternatives. Similarly, nuclear energy, while reliable and low-carbon, continues to play a modest role in the energy mix. It is projected to contribute 3.00% of electricity production and 1.79% of installed capacity by 2025-26, indicating its stable but limited role in India's energy strategy (*see Figures 1.3. and 1.5.*).

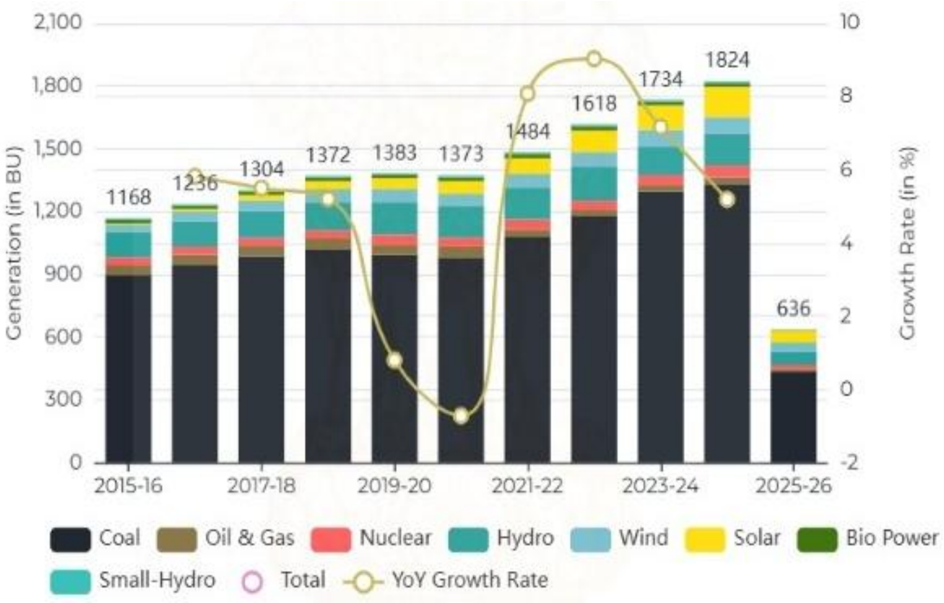


Figure 1.6. *Source-wise electricity generation trends in India in GW along with year on year growth rate for the years from 2015 to 2026. (as on 31st July 2025, Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited)*

The real transformation in India's power sector, however, lies in the remarkable growth of renewable energy sources. By 2025-26, renewable energy technologies such as solar, wind, hydro, small-hydro, and bio-power are set to contribute significantly to the country's energy production and installed capacity. The rapid adoption of renewables is driven by declining costs of renewable technologies, strong policy frameworks, and international commitments to reduce greenhouse gas emissions. Solar energy, in particular, is poised to play a pivotal role in reshaping the energy landscape. Its share in the total installed capacity is projected to rise sharply, reflecting its critical importance in achieving India's renewable energy targets (*see Figures 1.4. and 1.6.*).

Table 1.1. *Progress in renewable energy installations in India along with observed remarks.*

Source	Key Update	Remarks	Sources
Solar Energy	Solar power has emerged as a cornerstone of India's renewable energy strategy. By 2025-26, solar energy is expected to contribute 8.61% of electricity generation and 24.29% of installed capacity.	Overall, this growth reflects a rapid expansion and appears to be cost competitiveness	Ministry of New and Renewable Energy (MNRE) Central Electricity Authority (CEA) Nuclear Power Corporation of India Limited (NPCIL)
Wind Energy	Wind power is projected to account for 7.27% of electricity generation and 10.64% of installed capacity.	Recent years it gained huge attention making it another key pillar of India's renewable energy portfolio.	
Hydropower	Hydropower, including both large and small-hydro projects, contributes a stable share to the energy mix, projected at 9.63% of electricity generation and 10.13% of installed capacity in 2025-26.	Its role as a consistent and dispatchable power source is critical for grid stability.	

Bio-Power	Bio-power contributes 0.47% to electricity generation and 2.37% to installed capacity.	While its share remains relatively small, it offers opportunities for leveraging agricultural and industrial waste for energy production.	

1.2. How is solar energy is placed in India's power sector?

If we look at *Table 1.1*. summary, among Among all renewable energy sources, solar energy has emerged as the centerpiece of India's energy transition, playing a pivotal role in reshaping the country's energy landscape. India's geographical advantage, with abundant sunlight available for most of the year, positions the country as an ideal location for solar energy generation. The nation receives approximately 5,000 trillion kWh of solar radiation annually, with daily solar insolation levels ranging from 4 to 7 kWh/m^2 across most regions. This vast solar potential, coupled with declining costs of solar photovoltaic (PV) technology, has made solar energy the fastest-growing segment in India's renewable energy portfolio. Solar energy has become a key driver of the country's clean energy expansion, supported by government initiatives such as the National Solar Mission, which aims to promote large-scale adoption of solar energy through subsidies, policy frameworks, and incentives for developers.

Over the past decade, solar energy installations in India have grown exponentially. These installations range from utility-scale solar parks to decentralized rooftop systems, providing flexibility and scalability in meeting diverse energy needs. One of the significant advantages of solar energy is its scalability, as capacity can be expanded quickly and cost-effectively. Solar panels can be installed incrementally, and the process is faster compared to other power generation systems, making it an attractive option for both urban and rural applications. Additionally, off-grid solar systems have enabled electricity access in remote areas that are not connected to the main grid, supporting rural electrification and improving the quality of life for millions. Decentralized systems, where power is generated and consumed locally, have also reduced transmission losses, enhancing energy efficiency and reliability.

From a security-of-supply perspective, solar energy offers considerable advantages over conventional fossil fuels. Solar energy is widely accessible and abundant, unlike finite fossil fuel resources that are subject to price volatility and geopolitical risks. This makes solar energy a more secure and sustainable energy source for India, reducing dependency on imported fuels and contributing to energy independence. Furthermore, solar energy plays a critical role in addressing broader challenges such as energy security, climate change mitigation, and the reduction of carbon emissions. By reducing reliance on coal and other fossil fuels, solar energy helps India fulfill its international climate commitments under the Paris Agreement and contributes to a cleaner and more sustainable energy future.

Despite its rapid growth and transformative potential, the integration of solar energy into India's power grid presents several challenges. Solar energy is inherently intermittent, as it depends on sunlight, which varies across regions and seasons. This intermittency necessitates the development of advanced energy storage technologies, such as battery systems, to ensure a stable and reliable supply of electricity. Additionally, grid modernization is required to accommodate the increasing share of solar power, particularly in terms of balancing supply and demand and managing peak loads. Investments in infrastructure, policy measures, and technological innovations will be crucial to overcoming these barriers and unlocking the full potential of solar energy.

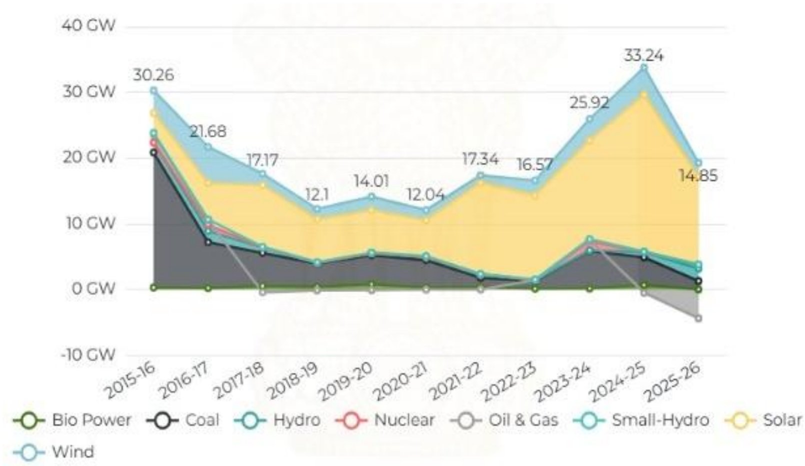


Figure 1.7. *Breakdown of net electricity capacity additions (in GW from 2015 to 2026) highlitigng the uptak of solar energy in India's power sector. (as on 31st July 2025, Data compiled from: MNRE- Ministry of New and Renewable Energy, CEA-Central Electricity Authority NPCIL- Nuclear Power Corporation of India Limited).*

Solar energy's impact on India's energy landscape is already evident in the electricity capacity addition trends of the last decade. A closer examination of source-specific capacity additions reveals that solar energy has consistently outpaced other renewable sources, establishing itself as a cornerstone of India's energy transition (see *Figure 1.7.*). By 2025-26, solar energy is expected to account for a substantial share of India's total installed capacity and electricity generation. This underscores its strategic importance in reducing the nation's reliance on coal, achieving energy security, and addressing environmental challenges. Solar energy, with its scalability, accessibility, and sustainability, is uniquely positioned to drive India's transition to a low-carbon energy future.

1.3. Motivation and the aim of the dissertation

India's commitments under the Paris Agreement and its ambitious renewable energy targets, including achieving 500 GW of non-fossil fuel capacity by 2030, underscore its urgency to adopt cleaner energy solutions. Among renewable energy sources, solar energy, particularly in the form of PV power plants, has emerged as a cornerstone of this transition. The motivation behind this dissertation arises from the critical need to explore the strategic adoption of photovoltaic power plant installation variants in India's electricity sector to create sustainable communities while addressing the nation's energy, environmental, and developmental challenges.

India's geographical advantage, with abundant solar radiation and favorable climatic conditions, positions it as a global leader in solar energy potential. Despite significant progress in solar energy deployment, the potential remains underutilized given the country's vast energy needs and the challenges of integrating solar power effectively into the grid. The motivation for this research stems from the recognition that different photovoltaic power plant installation variants—such as utility-scale solar parks, rooftop solar systems, and decentralized off-grid installations—offer unique benefits and trade-offs. These installation variants play distinct roles in addressing the diverse energy requirements of urban and rural areas, reducing transmission losses, improving energy access, and fostering decentralized energy generation. However, their strategic adoption requires a nuanced understanding of technical, economic, environmental, and socio-political dimensions. Another key driver of this research is the potential of PV power plants to contribute to the creation of sustainable communities. Solar energy systems can enable sustainable development by reducing greenhouse gas emissions, providing reliable energy access in underserved regions, and supporting economic growth through job creation in the renewable energy sector. Yet, barriers such as high initial costs, land acquisition challenges, grid infrastructure limitations, and policy inconsistencies hinder the widespread adoption of photovoltaic systems in India. Addressing these barriers and identifying strategic frameworks for the deployment of PV power plants is crucial for maximizing their contribution to India's energy transition and sustainability goals.

The aim of this dissertation is to explore the strategic adoption and deployment of photovoltaic power plant installation variants in India's electricity sector to foster the development of sustainable communities. The research seeks to examine how different PV power plant configurations can address India's unique energy challenges, contribute to decarbonization goals, and support socio-economic development. By analyzing the technical, economic, and policy aspects of these variants, the dissertation aims to provide actionable insights and recommendations for optimizing their adoption across diverse geographic and demographic contexts in India.

1.4. Objectives and the Disseration Outline

The primary objective of this dissertation is to investigate the strategic adoption and deployment of solar PV power plant installation variants in India's electricity sector to contribute to sustainable community development. This overarching goal is supported by the following specific objectives:

- To conduct a detailed literature review to find the various PV installation variants possible and then conduct the feasbility assessment of photovoltaic installation variants. As a part of this objective, I intend to evaluate the technical, economic, and environmental characteristics of different PV power plant installation variants, including utility-scale solar parks, rooftop solar systems, and decentralized off-grid installations, within the Indian energy context.
- To analysis of the Role of PV in India’s Electricity Sector: To examine the contribution of photovoltaic systems to India’s energy mix, focusing on their potential to reduce reliance on fossil fuels, improve energy access, and enhance grid efficiency.
- Identification of Barriers and Challenges: To identify the technical, financial, policy, and social barriers that hinder the large-scale adoption of PV power plants in India and to explore the implications of these challenges for sustainable energy transitions.
- To explore var Strategic Frameworks for Adoption: To propose strategic frameworks and actionable recommendations for optimizing the adoption of photovoltaic power plants, tailored to India’s geographic, economic, and demographic diversity.

This section presents a structured overview of the thesis, outlining the organization and scope of each chapter to guide the reader through the progression of this research.

Chapter 1: Introduction, this chapter provides introduction to India's energy sector on understanding on how the solar energy is placed.

Chapter 2: Review of the Literature, this chapter will delve into existing literature review related to solar energy power plants, policies, incentives and others.

Chapter 3: Framework and Methodology, in this chapter, the research methods used to explore the research questions are explained.

Chapter 4: Results and Discussion, this chapter will present results on operational challenges and technology choices, strategies for achieving sustainability, and offsetting benefits along with survey based narratives and validations.

Chapter 5: Conclusion and Future Research Proposition, the final chapter will summarize the entire study, reiterating the key findings and discussing how future research can be taken in the field.

CHAPTER 2

REVIEW OF THE LITERATURE

This chapter presents a comprehensive review of the literature to establish the historical development, current status, and strategic importance of solar energy in India, situating it within both global and national contexts. The review explores the evolution of solar energy technologies, the types of solar power plants deployed globally and in India, and the policy frameworks that have driven the growth of the sector. By synthesizing existing knowledge, this chapter identifies research gaps and provides a foundation for investigating the strategic adoption of photovoltaic (PV) power plant installation variants in India's energy sector.

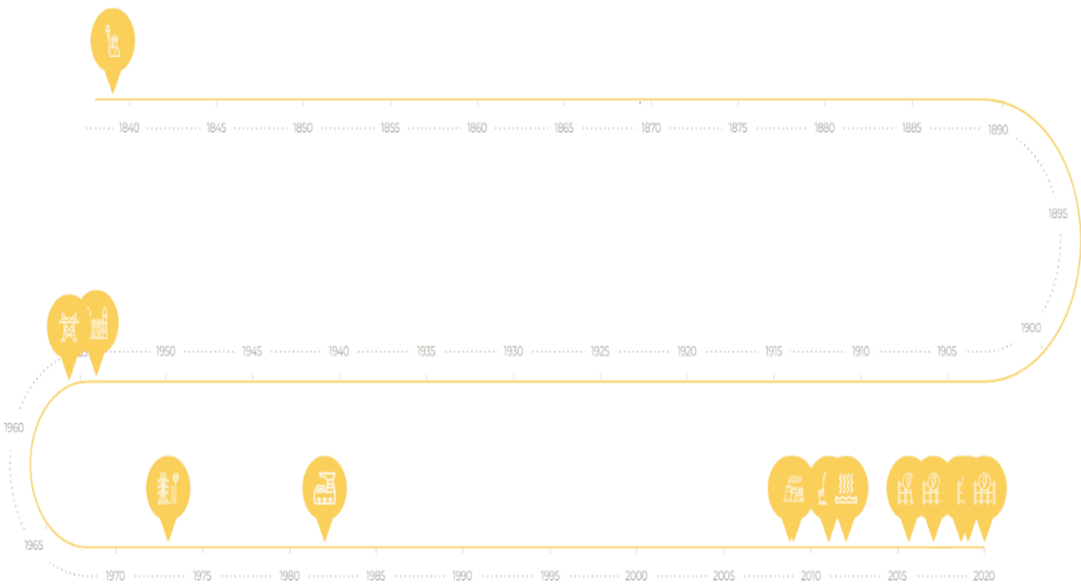


Figure 2.1. *Timeline showing the historical journey of solar energy. [note: India's journey started from year 2008 onwards in solar installations, Source URL: Niti Aayog]*

The literature reveals that solar energy has been harnessed for centuries dates back to 1840s, with early applications dating back to the use of solar thermal technologies for heating and cooking. However, the modern photovoltaic (PV) solar cell was first developed in the 1950s, marking the beginning of solar energy as a viable source of electricity. Globally, the adoption of solar energy gained momentum in the late 20th century, driven by advancements in PV technology, the oil crises of the 1970s, and increasing environmental awareness (*see Figure 2.1.*). In India, solar energy began to gain prominence in the early 2000s, with the launch of initiatives aimed at promoting renewable energy (*see Figure 2.2.*). The establishment of the Ministry of New and Renewable Energy (MNRE) and the launch of the National Solar Mission in 2010 were pivotal moments that accelerated the deployment of solar technologies in the country (MNRE, 2010).

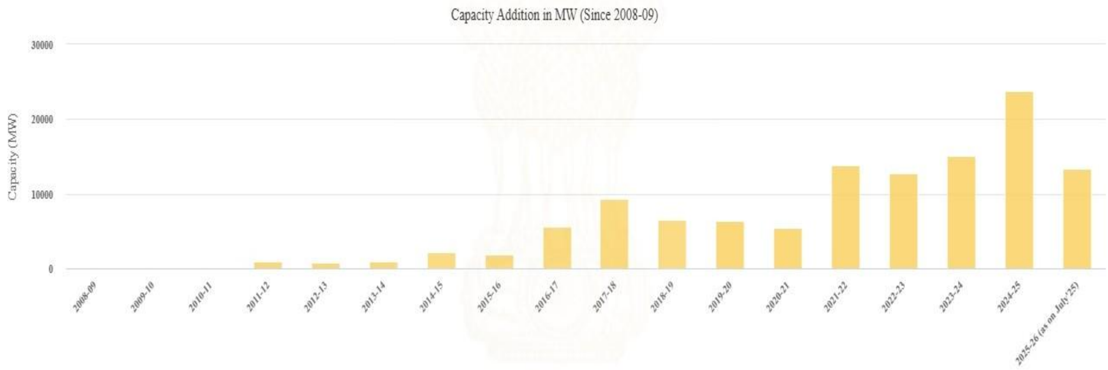


Figure 2.2. *Timeline showing the historical journey of solar energy (Data Source: NITI Aayog).*

2.1. Overview of state level solar energy installation and their progress in India

India has set ambitious targets to increase its renewable energy capacity, including a target of achieving 175 GW of renewable energy by 2022, with 100 GW coming from solar energy. The Indian government has launched several initiatives to promote solar energy, including the Jawaharlal Nehru National Solar Mission and the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme, which aims to install solar pumps and other solar-based decentralized applications in rural areas. As a result of these initiatives, millions of people in Indian communities have benefited from solar energy-based decentralized and distributed applications, such as solar home lighting systems, solar streetlights, and solar pumps. These applications have helped to meet the lighting, cooking, and other energy needs of communities in an eco-friendly and sustainable way, while also Solar energy has emerged as a crucial component of India's energy mix, supporting the government's objective of achieving sustainable growth while also addressing energy security concerns. The Indian government has implemented several policies and initiatives to promote solar energy, including the National Solar Mission, which aims to achieve 100 GW of solar energy by 2022, and the Solar Parks scheme, which facilitates the development of large-scale solar.

The Indian government has implemented various programs and initiatives to promote the use of solar energy in the country, including the ones you have mentioned. These programs have helped to accelerate the deployment of solar energy and make it more accessible and affordable for the masses. As of November 2022, India's installed solar energy capacity has increased to approximately 61.97 GW, making it the fourth largest country in the world in terms of solar power capacity. The Indian government has set an ambitious target of achieving 450 GW of renewable energy capacity, including 280 GW of solar energy, by 2030. The growth of solar energy in India has been supported by a decline in the cost of solar power tariffs, which have reached grid parity with conventional power tariffs in many parts of the country. *Table 2.1* indicated the capacity of solar plants installed in India state wise. As of 31-12-2022, the total installed capacity of solar PV plants is 63,303 MW.

Table 2.1. State wise installed capacity of Solar Power Plants. (Data Source: MNRE - Ministry of New and Renewable Energy)

The Indian States	**Installed Capacity (As on March 2021)**	**Installed Capacity (As on 31.12.2022)**
Andhra Pradesh	4203 MW	9549.52 MW
Arunachal Pradesh	5.61 MW	144.63 MW
Assam	42.99 MW	184.03 MW
Bihar	159.51 MW	389.61 MW
Chhattisgarh	252.48 MW	1149.34 MW
Goa	7.44 MW	26.79 MW
Gujarat	4430.82 MW	18561.48 MW
Haryana	407.83 MW	1323.05 MW
Himachal Pradesh	42.73 MW	1058.30 MW
Jammu and Kashmir	20.73 MW	193.58 MW
Jharkhand	52.06 MW	103.26 MW
Karnataka	5355.17 MW	16336.60 MW
Kerala	257 MW	1019.87 MW
Madhya Pradesh	2463.22 MW	5874.53 MW
Maharashtra	2289.97 MW	11676.76
Manipur	6.36 MW	17.73 MW
Meghalaya	0.12 MW	50.48 MW
Mizoram	1.53 MW	49.48 MW
Nagaland	1 MW	34.71 MW
Odisha	401.72 MW	627.52 MW
Punjab	959.5 MW	1828.25 MW
Rajasthan	5732.58 MW	2117.50 MW
Sikkim	0.07 MW	59.79 MW
Tamil Nadu	4475.21 MW	17514.13 MW
Telangana	3953.12 MW	5089.64 MW
Tripura	9.41 MW	32.68 MW
Uttar Pradesh	1712.5 MW	4727.15 MW
Uttarakhand	0 W	933.72 MW
West Bengal	149.84 MW	602.03 MW

A list of few major solar power plants located in Indian states, with their capacity is displayed in Table 2.2.

Table 2.2. Major Solar Power Projects in India. (Source: data Compiled from the MNRE-Ministry of New and Renewable Energy's Energy Statistics Report, Govt. of India)

State	Location	Capacity	Developer
Andhra Pradesh	Ananthapuramu-I Solar Park	1500	AP Solar Power Corporation Pvt. Ltd. (APSPCL), JVC of SECI, APGENCO and NREDCAP
	Kurnool Solar Park	1000	
	Kadapa Solar Park	1000	
	Ananthapuramu-II Solar Park	500	
	Hybrid Solar Wind Park	160	
Arunachal Pradesh	Lohit Solar Park	20	Arunachal Pradesh Energy Development Agency (APEDA)
Gujarat	Radhnesada Solar Park	700	Gujarat Power Corporation Limited (GPCL)
	Harsad Solar Park	350	
	Dholera Solar Park Ph-I	1000	
	Dholera Solar Park Ph-II	4000	Solar Energy Corporation of India (SECI)
Himachal Pradesh	Kaza Solar Park	1000	JVC of SJVN & Govt of HP
Jharkhand	Floating Solar Park	150	Solar Energy Corporation of India (SECI)
Karnataka	Pavagada Solar Park	2000	Karnataka Solar Power Development Corporation Pvt. Ltd. (KSPDCL), JVC of KREDL & SECI
Kerala	Kasargod Solar Park	105	Renewable Power Corporation of Kerala Limited (RPCKL), JVC of SECI
Madhya Pradesh	Rewa Solar Park	750	

	Mandsaur Solar Park	250	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Neemuch	500	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Agar	550	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Shajapur	450	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Omkareswar Floating Solar Park	600	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Chhattarpur Solar Park	950	Rewa Ultra Mega Solar Limited (RUMSL), JVC of MPNRED & SECI
	Barethi Solar Park	550	NTPC
Maharashtra	Sai Guru Solar Park (Pragat)	500	M/s Sai Guru Mega Solar Park Pvt. Ltd. (formerly M/s Pragat Akshay Urja Ltd.)
	Patoda Solar Park (Paramount)	150	M/s Paramount Solar Power Pvt. Ltd. (formerly M/s K. P. Power Pvt. Ltd.)
	Dondaicha Solar Park	250	Maharashtra State Electricity Generating Company Ltd. (MAHAGENCO)
Manipur	Bukpi Solar Park	20	Manipur Tribal Development Corpn. Ltd. (MTDCL)
Meghalaya	Solar Park in Meghalaya	20	Meghalaya Power Generation Corporation Ltd (mepgcl)
Mizoram	Vankal Solar Park	20	Power & Electricity Department
Odisha	Solar Park by NHPC	40	NHPC Limited
	Solar Park by NHPC	100	NHPC Limited
Rajasthan	Bhadla-II Solar Park	680	Rajasthan Solar Park Development Company Ltd. (RSDCL)

	Bhadla-III Solar Park	1000	M/s Surya Urja Company of Rajasthan Ltd (SUCRL) JVC of State Govt
	Bhadla-IV Solar Park	500	M/s Adani Renewable Energy Park Rajasthan Limited (AREPRL) JVC of State Govt
	Phalodi-Pokaran Solar Park	750	M/s Essel Surya Urja Company of Rajasthan Limited (ESUCRL) JVC of State Govt
	Fatehgarh Phase-1B Solar Park	421	M/s Adani Renewable Energy Park Rajasthan Limited (AREPRL) JVC of State Govt
	Nokh Solar Park	925	Rajasthan Solar Park Development Company Ltd. (RSDCL)
Uttar Pradesh	Solar Park in UP	440	Lucknow Solar Power Development Corporation Ltd. (LSPDCL) JVC of UPNEDA & SECI
	Jalaun Solar Park	1200	BSUL

Under the National Solar Mission, the government has set a goal for the country of 100 GW of installed solar power by 2022. (NSM). The goal will be accomplished using a variety of policy choices, supportive systems, programmes, etc. Discoms from different States and uts have received a total of Rs. 1134.47 crore in FY 2021–2022 (as on 31.12.2021) for installing new grid integrated roof top and small solar power plants. The total amount is distributed over all the states for the new solar PV installations around 3,339.62 MW.

Table 2.4. New allotment for Solar PV as on 31-12-2022.

The Indian States	Aggregated allotted capacity in (MW)
Andhra Pradesh	25
Arunachal Pradesh	0

Assam	2
Bihar	25
Chhattisgarh	10
Goa	80
Gujarat	1188.86
Haryana	46.50
Himachal Pradesh	15
Jammu and Kashmir	20.00
Jharkhand	60.70
Karnataka	372
Kerala	250
Madhya Pradesh	45
Maharashtra	531.48
Manipur	1
Meghalaya	70
Mizoram	1.50
Nagaland	4.80
Odisha	4
Punjab	80
Rajasthan	70
Sikkim	2
Tamil Nadu	55
Telangana	37.28
Tripura	1
Uttar Pradesh	98
Uttarakhand	28
West Bengal	50
Total	**3,339.62**

2.2. Overview of state level solar power projects under construction in India

India's solar energy sector has made remarkable progress, with a substantial pipeline of under-construction projects across states and union territories (*see Table 2.5.*).

Table 2.5. State level solar power projects under construction in India after 2022 along with commissioning date and pipeline capacity with agency responsible for implementing. (Data Source: NPP-National Power Portal and CEA-Central Electricity Authority)

State	**Scheduled Commissioning date**	**Anticipated Date of Commissioning**	**Pipeline Capacity (MW)**	**Implementing Agency**
Maharashtra	2024-03-31T00:00:00.000Z		12.5	TP Saturn Limited
Madhya Pradesh	2027-03-31T00:00:00.000Z	2027-03-31T00:00:00.000Z	500	Avaada MP Solar Private Limited
Madhya Pradesh	2026-09-30T00:00:00.000Z	2026-09-30T00:00:00.000Z	750	Avaada MP Sustainable Private Limited
Gujarat	2025-03-31T00:00:00.000Z	2025-06-30T00:00:00.000Z	70	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Rajasthan	2023-12-07T00:00:00.000Z	2026-05-01T00:00:00.000Z	400	JGRJ Two Solar Private Limited
Rajasthan	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	600	Adani Renewable Energy Holding Seventeen Private Limited
West Bengal	2025-09-30T00:00:00.000Z	2026-03-31T00:00:00.000Z	150	Green Valley Renewable Energy
Chhattisgarh	2025-03-31T00:00:00.000Z	2027-01-31T00:00:00.000Z	26	National Thermal Power Corporation(NTPC)
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	196	MSKVY Tenth Solar Private Limited
Gujarat	2028-02-01T00:00:00.000Z	2028-02-01T00:00:00.000Z	400	ReNew Solar Power Private Limited
Gujarat	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	150	Serentica Renewables India Private Limited
Rajasthan	2028-06-01T00:00:00.000Z	2028-06-01T00:00:00.000Z	300	Juniper Green India Six Private Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-09-30T00:00:00.000Z	300	IB Vogt Solar Seven Private Limited

Rajasthan	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	217	Proteus Energy Private Limited
Bihar	2023-11-26T00:00:00.000Z	2025-05-31T00:00:00.000Z	75	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Andhra Pradesh	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	100	Andhra Pradesh Solar Power Corporation Limited(a JV of NREDCAP, APGENCO & SECI)
Rajasthan	2025-09-13T00:00:00.000Z	2025-06-30T00:00:00.000Z	200	Avaada Solar Power Private Limited
Rajasthan	2027-12-01T00:00:00.000Z	2027-12-01T00:00:00.000Z	50	Juniper Green Energy Private Limited
Rajasthan	2025-12-27T00:00:00.000Z	2025-12-27T00:00:00.000Z	300	Khidrat Renewable Energy Private Limited
Gujarat/Andhra Pradesh/Rajasthan	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	250	Acme Renewtech Sixth Private Limited
West Bengal	2024-08-03T00:00:00.000Z	2025-05-30T00:00:00.000Z	14	Damodar Valley Corporation (DVC)
Rajasthan	2024-10-31T00:00:00.000Z	2025-10-31T00:00:00.000Z	300	TP SAURYA LIMITED
Gujarat	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	300	Avaada GJSustainable 2 Private Limited
Rajasthan	2030-03-31T00:00:00.000Z	2030-03-31T00:00:00.000Z	2000	Adani Renewable Energy Park Rajasthan Limited
Rajasthan	2023-07-28T00:00:00.000Z	2026-08-22T00:00:00.000Z	150	JGRJ One Solar Private Limited
Rajasthan	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	150	Juniper Green Cosmic Private Limited
Rajasthan	2023-11-11T00:00:00.000Z	2025-08-31T00:00:00.000Z	300	National Hydroelectric Power Corporation Limited
Maharashtra	2025-05-01T00:00:00.000Z	2025-07-31T00:00:00.000Z	100	ReNew Solar Power Private Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-09-30T00:00:00.000Z	300	ReNew Solar (Shakti Three) Private Limited
Gujarat	2026-10-31T00:00:00.000Z	2026-12-31T00:00:00.000Z	750	Adani Renewable Energy Holding Four Limited
Karnataka	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	25	Reliance Jio Infocomm Limited
Gujarat	2024-10-28T00:00:00.000Z	2027-12-31T00:00:00.000Z	300	Sprng Green Power Private Limited

Gujarat/Andhra Pradesh	2025-06-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	100	Ayana Renewable Power Four Private Limited
Rajasthan	2030-03-31T00:00:00.000Z	2030-03-31T00:00:00.000Z	900	Purvah Green Power Private Limited (Developer Company)
Rajasthan	2026-02-01T00:00:00.000Z	2026-02-01T00:00:00.000Z	300	Juniper Green Beta Private Limited
Karnataka/Gujarat	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	280	ACME Hybrid Urja Private Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-05-31T00:00:00.000Z	210	ReNew Surya Pratap Private Limited
Rajasthan	2026-03-01T00:00:00.000Z	2026-03-01T00:00:00.000Z	300	Helia Energy Park Private Limited
Rajasthan	2026-04-03T00:00:00.000Z	2026-04-03T00:00:00.000Z	300	SPV - HRP Green Power Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	100	Amplus Kaveri Solar Private Limited
Rajasthan	2026-04-17T00:00:00.000Z	2025-12-31T00:00:00.000Z	250	Apraava Energy Private Limited
Maharashtra	2026-12-31T00:00:00.000Z	2026-12-31T00:00:00.000Z	250	Maharashtra State Electricity Generating Co. Limited -MAHAGENCO
Rajasthan	2029-01-01T00:00:00.000Z	2029-01-01T00:00:00.000Z	800	ReNew Solar (Shakti Six) Private Limited(400+400)
Uttar Pradesh	2025-02-28T00:00:00.000Z	2025-06-30T00:00:00.000Z	20	National Thermal Power Corporation(NTPC)
Rajasthan	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	100	Sourya Manthan Renewable Energy Private Limited
Rajasthan	2025-09-30T00:00:00.000Z	2025-09-30T00:00:00.000Z	100	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Gujarat	2025-02-06T00:00:00.000Z	2025-07-31T00:00:00.000Z	100	Martial Solren Private Limited
Rajasthan	2028-12-31T00:00:00.000Z	2028-12-31T00:00:00.000Z	300	Avaada RJSustainable Private Limited
Gujarat	2022-05-16T00:00:00.000Z	2025-12-31T00:00:00.000Z	52	HR Sabarmati Private Limited
Gujarat	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	550	NTPC Renewable Energy Limited
Maharashtra	2024-08-29T00:00:00.000Z		3.12	TP Godavari Solar Limited

West Bengal	2024-08-03T00:00:00.000Z		10	Damodar Valley Corporation (DVC)
Rajasthan	2025-09-15T00:00:00.000Z	2025-09-15T00:00:00.000Z	200	Martial Solren Private Limited
Gujarat	2025-08-16T00:00:00.000Z	2025-07-31T00:00:00.000Z	300	Damodar Valley Corporation (DVC)
Maharashtra	2022-09-13T00:00:00.000Z	2025-07-31T00:00:00.000Z	9.29	Huoban Private Limited
Gujarat	2025-10-30T00:00:00.000Z	2025-10-30T00:00:00.000Z	200	Avaada GJSustainable Private Limited [Lakadiya-SECI]
Maharashtra	2025-02-28T00:00:00.000Z		13	National Thermal Power Corporation(NTPC)
Rajasthan	2030-03-31T00:00:00.000Z	2030-03-31T00:00:00.000Z	1200	ReNew Solar Power Private Limited
Gujarat	2023-11-30T00:00:00.000Z	2026-03-31T00:00:00.000Z	400	NTPC Renewable Energy Limited
Andhra Pradesh	2029-01-01T00:00:00.000Z	2029-01-01T00:00:00.000Z	900	Purvah Green Power Private Limited (Developer Company)
Rajasthan	2026-08-31T00:00:00.000Z	2026-08-31T00:00:00.000Z	150	Adani Solar Energy AP Three Limited
Gujarat	2025-05-31T00:00:00.000Z	2025-05-31T00:00:00.000Z	450	NTPC Renewable Energy Limited
Gujarat	2029-03-01T00:00:00.000Z	2029-03-01T00:00:00.000Z	200	Juniper Green Energy Private Limited
Maharashtra	2026-11-21T00:00:00.000Z	2026-11-21T00:00:00.000Z	500	Avaada MHRenewable1 Private Limited
Rajasthan	2030-12-31T00:00:00.000Z	2030-12-31T00:00:00.000Z	1100	Avaada Suryaenergy Private Limited
Assam	2025-08-06T00:00:00.000Z	2025-08-06T00:00:00.000Z	120	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Gujarat	2025-03-31T00:00:00.000Z		60	NTPC Renewable Energy Limited
Rajasthan	2026-08-22T00:00:00.000Z	2026-05-30T00:00:00.000Z	900	Serentica Renewables India Private Limited 5, Serentica Renewables India Private Limited 8, Serentica Renewables India Private Limited 9
Andhra Pradesh	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	750	Andhra Pradesh Solar Power Corporation Limited(a JV of NREDCAP, APGENCO & SECI)
Kerala	2026-02-06T00:00:00.000Z	2026-02-06T00:00:00.000Z	50	National Hydroelectric Power Corporation Limited

Rajasthan	2029-12-31T00:00:00.000Z	2029-12-31T00:00:00.000Z	717	Adani Renewable Energy Holding Four Limited
Maharashtra	2024-12-02T00:00:00.000Z		3.12	TP Mercury Limited
Gujarat	2026-12-31T00:00:00.000Z	2026-12-31T00:00:00.000Z	300	Avaada GJGreen Private Limited
Maharashtra	2025-03-31T00:00:00.000Z	2025-05-31T00:00:00.000Z	20	Ortusun Renewables
Gujarat	2028-04-01T00:00:00.000Z	2028-04-01T00:00:00.000Z	300	Purvah Green Power Private Limited (Developer Company)
Rajasthan	2028-03-31T00:00:00.000Z	2028-03-31T00:00:00.000Z	140	Renew Solar Power Private Limited
Rajasthan	N.A.	2026-12-31T00:00:00.000Z	50	TEQ Green Power XVI Private Limited
Maharashtra	2028-06-01T00:00:00.000Z	2028-06-01T00:00:00.000Z	400	Juniper Green Energy Private Limited
Gujarat	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	3325	Gujarat State Electricity Corporation Limited
Rajasthan	2026-10-15T00:00:00.000Z	2026-10-15T00:00:00.000Z	300	Radiant Star Solar Park Private Limited
Rajasthan	2025-12-27T00:00:00.000Z	2025-12-27T00:00:00.000Z	300	Shikhar Surya (One) Private Limited
Rajasthan	2024-06-30T00:00:00.000Z		380	ABC RJ Land 01 Private Limited
Rajasthan	N.A.	2026-12-31T00:00:00.000Z	120	TEQ Green Power XIII Private Limited
Rajasthan	N.A.	2026-12-31T00:00:00.000Z	500	Inox Wind Energy Limited
Maharashtra	2026-05-31T00:00:00.000Z	2026-05-31T00:00:00.000Z	200	Skadar Solar Private Limited
Rajasthan	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	50	Juniper Nirjara Energy Private Limited
Rajasthan	2030-03-31T00:00:00.000Z	2030-03-31T00:00:00.000Z	1049	Adani Renewable Energy Holding Four Limited
Gujarat	N.A.	2025-06-20T00:00:00.000Z	200	Teq Green Power Private Limited
Madhya Pradesh	2027-05-31T00:00:00.000Z	2027-05-31T00:00:00.000Z	200	Asnen Solar Private Limited

Maharashtra	2024-03-04T00:00:00.000Z		26	TP Adhrit Solar Limited
Rajasthan	2024-07-31T00:00:00.000Z		400	Abc Renewable Energy RJ-01 Privatelimited
Rajasthan	N.A.	2025-06-30T00:00:00.000Z	205	Energizent Power Private Limited
Maharashtra	2024-01-04T00:00:00.000Z		12.5	TP Green Nature Limited
Maharashtra	2028-06-01T00:00:00.000Z	2028-06-01T00:00:00.000Z	300	Juniper Green Gem Private Limited
Rajasthan	2027-03-31T00:00:00.000Z	2027-03-31T00:00:00.000Z	50	Adani Renewable Energy Holding Eighteen Limited(AREH18L)
Gujarat	2026-01-31T00:00:00.000Z	2026-03-02T00:00:00.000Z	600	National Hydroelectric Power Corporation Limited
Chhattisgarh	2024-03-31T00:00:00.000Z		67.5	Aditya Birla Renewables Energy Limited (ABReEL)
Maharashtra	2025-03-31T00:00:00.000Z	2025-09-30T00:00:00.000Z	50	Ctrls Datacenters Limited
Andhra Pradesh	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	250	Ayana Kadapa Renewable Power Private Limited
Gujarat	2026-05-30T00:00:00.000Z	2026-05-30T00:00:00.000Z	150	Malaren Solar Private Limited
Karnataka	2028-09-01T00:00:00.000Z	2028-09-01T00:00:00.000Z	300	Purvah Green Power Private Limited (Developer Company)
Gujarat	2024-12-31T00:00:00.000Z	2027-01-31T00:00:00.000Z	1200	NTPC Renewable Energy Limited
Gujarat	2025-05-31T00:00:00.000Z	2027-01-31T00:00:00.000Z	630	NTPC Renewable Energy Limited
Rajasthan	2028-12-31T00:00:00.000Z	2028-12-31T00:00:00.000Z	250	Adani Renewable Energy Holding Four Limited
N.A.	2025-06-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	300	SAEL SOLAR MHP2 Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	231	MSKVY Eleventh Solar Private Limited
Gujarat	2022-04-16T00:00:00.000Z		120	HR Sabarmati Private Limited
Gujarat	2027-03-31T00:00:00.000Z	2027-03-31T00:00:00.000Z	700	Gujarat State Electricity Corporation Limited

Uttar Pradesh	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	1400	NTPC Renewable Energy Limited
Maharashtra	2024-01-08T00:00:00.000Z		18.62	Nivede Windfarm Limited
Gujarat	2026-01-31T00:00:00.000Z	2026-01-31T00:00:00.000Z	200	NTPC Renewable Energy Limited
Gujarat	2027-03-31T00:00:00.000Z	2027-03-31T00:00:00.000Z	270	Clean Renewable Energy Hybrid Eleven Private Limited(SPV of Hero Solar Energy Private Limited)
Rajasthan	2026-08-30T00:00:00.000Z	2026-08-30T00:00:00.000Z	300	Frugal Energy Private Limited
Gujarat	2026-03-31T00:00:00.000Z	2027-01-31T00:00:00.000Z	225	NTPC Renewable Energy Limited
Rajasthan	2028-12-01T00:00:00.000Z	2028-12-01T00:00:00.000Z	600	Juniper Green Energy Private Limited
Rajasthan	2026-12-01T00:00:00.000Z	2026-12-01T00:00:00.000Z	300	Juniper Green Stellar Private Limited
Uttar Pradesh	2025-12-31T00:00:00.000Z	2025-12-31T00:00:00.000Z	600	M/s Hinduja Renewables Energy Private Limited
Rajasthan	2027-06-01T00:00:00.000Z	2027-06-01T00:00:00.000Z	4200	ReNew Solar Power Private Limited
Rajasthan	2026-04-25T00:00:00.000Z	2026-04-25T00:00:00.000Z	250	Sprng Power Private Limited
Gujarat	2026-06-30T00:00:00.000Z	2026-06-30T00:00:00.000Z	115	Adani Renewable Energy Eight Limited
Maharashtra	2024-11-15T00:00:00.000Z		4.4	TP Solapur Solar Limited
Karnataka	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	300	ACME Omega Urja Private Limited
Gujarat	2022-07-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	137	NTPC Renewable Energy Limited
Gujarat	2024-02-28T00:00:00.000Z	2025-09-30T00:00:00.000Z	500	Adani Renewable Energy Holding Four Limited
Rajasthan	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	300	M/s. Essel Surya Urja Company of Rajasthan Limited - ESUCRL- A JV of Rajasthan State Govt. and Essel Infraprojects Limited
Gujarat	2025-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	200	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Gujarat	2025-03-31T00:00:00.000Z		600	Gujarat State Electricity Corporation Limited

Rajasthan	2030-03-01T00:00:00.000Z	2030-03-01T00:00:00.000Z	130	Juniper Green Energy Private Limited
Rajasthan	2025-07-31T00:00:00.000Z	2026-08-31T00:00:00.000Z	300	NEEPCO Limited (SPD)
Gujarat	2023-03-29T00:00:00.000Z	2025-12-31T00:00:00.000Z	158	HR Sabarmati Private Limited
Uttar Pradesh	2025-09-30T00:00:00.000Z	2025-09-30T00:00:00.000Z	50	Amplus Tungabhadra Private Limited
Gujarat	2027-09-01T00:00:00.000Z	2027-09-01T00:00:00.000Z	1200	ReNew Solar Power Private Limited
Rajasthan	2026-06-27T00:00:00.000Z	2026-06-27T00:00:00.000Z	300	Furies Solren Private Limited
Maharashtra	2025-04-01T00:00:00.000Z		150	Tata Power Renewable Energy Limited
Rajasthan	2026-11-01T00:00:00.000Z	2026-11-30T00:00:00.000Z	300	Renew Sun Power Private Limited
Rajasthan	2025-02-02T00:00:00.000Z		266	Adani Renewable Energy Park Rajasthan Limited – AREPRL – a JV of State Govt. & Adani Renewable Energy Park Limited
Rajasthan	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	50	Apraava Energy Private Limited
Rajasthan	2025-06-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	300	ACME Sikar Solar Private Limited
Andhra Pradesh	2026-12-31T00:00:00.000Z	2026-12-31T00:00:00.000Z	300	Solar Energy Corporation of India Limited (SECI)
Rajasthan	2030-03-01T00:00:00.000Z	2030-03-31T00:00:00.000Z	300	ReNew Solar Power Private Limited
Rajasthan	2030-12-31T00:00:00.000Z	2030-12-31T00:00:00.000Z	250	ReNew Solar Power Private Limited
Gujarat	2025-02-01T00:00:00.000Z		25	Bhargavi Renewable Private Limited
Rajasthan	2025-06-26T00:00:00.000Z	2025-06-26T00:00:00.000Z	417.8	Sprng Akshaya Urja Private Limited
Punjab/Himachal Pradesh	2025-07-07T00:00:00.000Z	2025-07-07T00:00:00.000Z	18	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Madhya Pradesh	2027-03-30T00:00:00.000Z	2027-03-30T00:00:00.000Z	900	Avaada KNClean Private Limited
Rajasthan	2025-03-31T00:00:00.000Z	2025-09-30T00:00:00.000Z	1000	Satluj Jal Vidyut Nigam Limited Green Energy Limited

Rajasthan	2027-01-31T00:00:00.000Z	2027-01-31T00:00:00.000Z	150	SPV - Deshraj Solar Energy Private Limited
Rajasthan	2026-06-30T00:00:00.000Z	2025-12-31T00:00:00.000Z	300	Apraava Energy Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	164	MSKVY Twentieth Solar Private Limited
Maharashtra	2024-10-01T00:00:00.000Z	2025-10-01T00:00:00.000Z	270	Tata Power Renewable Energy Limited
Rajasthan	2026-11-07T00:00:00.000Z	2027-01-25T00:00:00.000Z	250	Tejorupa Renewables India Project Private Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-09-30T00:00:00.000Z	400	ReNew Solar (Shakti Five) Private Limited
Rajasthan	2027-03-31T00:00:00.000Z	2027-03-31T00:00:00.000Z	300	CESC Limited (Developer Company)
Rajasthan	2030-03-31T00:00:00.000Z	2030-03-31T00:00:00.000Z	700	Avaada RJSustainable Private Limited
Rajasthan	2025-01-23T00:00:00.000Z		400	XL Xergi Power Private Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-05-31T00:00:00.000Z	210	ReNew Surya Jyoti Private Limited
Rajasthan	2026-08-01T00:00:00.000Z	2026-01-01T00:00:00.000Z	1400	Sunbreeze Renewables Nine Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	194	MSKVY Fifth Solar Private Limited
Rajasthan	2025-03-31T00:00:00.000Z	2025-06-30T00:00:00.000Z	490	National Thermal Power Corporation(NTPC)
Jharkhand/West Bengal	2025-03-31T00:00:00.000Z		310	Green Valley Renewable Energy
Rajasthan	2025-12-27T00:00:00.000Z	2025-06-30T00:00:00.000Z	44	Serentica Renewables India Private Limited 5
Rajasthan/Gujarat	2026-05-02T00:00:00.000Z	2026-05-02T00:00:00.000Z	250	ACME Surya Power Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	98	Avaada Sustainable Urja Private Limited
Madhya Pradesh	2023-06-25T00:00:00.000Z	2025-06-30T00:00:00.000Z	235	Talettutayi Solar Projects Nine Private Limited
Maharashtra	2025-08-31T00:00:00.000Z	2025-08-31T00:00:00.000Z	222	MSKVY First Kusum Private Limited

Gujarat	2028-06-01T00:00:00.000Z	2028-06-01T00:00:00.000Z	750	Juniper Green Energy Private Limited
Rajasthan	2027-04-30T00:00:00.000Z	2027-04-30T00:00:00.000Z	300	ReNew Solar Power Private Limited
Rajasthan/Gujarat	2026-05-21T00:00:00.000Z	2026-05-21T00:00:00.000Z	320	ACME Sun Power Private Limited
Maharashtra	2024-10-25T00:00:00.000Z		43.75	TP Samaksh Limited
Himachal Pradesh	2024-06-23T00:00:00.000Z	2027-12-31T00:00:00.000Z	15	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Rajasthan	2026-04-03T00:00:00.000Z	2026-04-03T00:00:00.000Z	300	HRP Green Power Private Limited (SPD)
Odisha	2025-06-05T00:00:00.000Z	2025-06-05T00:00:00.000Z	40	National Hydroelectric Power Corporation Limited
Rajasthan	2025-10-31T00:00:00.000Z	2025-10-31T00:00:00.000Z	1500	Adani Renewable Energy Holding Four Limited
Gujarat	2026-09-01T00:00:00.000Z	2026-09-01T00:00:00.000Z	300	ReNew Solar (Shakti Eight) Private Limited
Punjab	2025-06-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	100	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-09-30T00:00:00.000Z	100	ReNew Dinkar Jyoti Private Limited
Gujarat	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	250	Sprng Power Earth Private Limited
Jharkhand	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	100	Solar Energy Corporation of India Limited (SECI)
Karnataka	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	200	Indian Oil NTPC Green Energy Private Limited
Andhra Pradesh	2023-11-11T00:00:00.000Z	2025-08-31T00:00:00.000Z	100	National Hydroelectric Power Corporation Limited
Rajasthan	2025-09-19T00:00:00.000Z	2025-09-30T00:00:00.000Z	300	ReNew Samir Shakti Private Limited
Rajasthan	2026-11-11T00:00:00.000Z	2026-11-11T00:00:00.000Z	300	AM Green Energy Private Limited, Bikaner
Rajasthan	2024-05-15T00:00:00.000Z	2025-09-30T00:00:00.000Z	200	ReNew Dinkar Urja Private Limited
Madhya Pradesh	2025-06-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	170	Rewa Ultra Mega Solar Limited RUMSL- a JV of MPUVN and SECI

Gujarat	2025-03-31T00:00:00.000Z	2025-09-30T00:00:00.000Z	360	Satluj Jal Vidyut Nigam Limited Green Energy Limited
Karnataka	2025-09-16T00:00:00.000Z	2025-09-16T00:00:00.000Z	350	Ircon Renewable Power Limited
Maharashtra	2024-01-03T00:00:00.000Z		28.12	TP Alpha Limited
Andhra Pradesh	2020-06-29T00:00:00.000Z	2026-02-28T00:00:00.000Z	250	Sprng Soura Kiran Private Limited
Karnataka	N.A.	2026-12-31T00:00:00.000Z	70	TEQ Green Power XVI Private Limited
Rajasthan	2026-03-01T00:00:00.000Z	2026-11-30T00:00:00.000Z	600	ReNew Solar Power Private Limited (2 x 300)
Maharashtra	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	400	Avaada SunEnergy Private Limited
Rajasthan	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	250	Acme Renewtech Fifth Private Limited
Jharkhand	2025-07-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	160	Green Valley Renewable Energy
Rajasthan	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	340	Abu Renewables India Private Limited
Gujarat	2026-04-30T00:00:00.000Z	2026-04-30T00:00:00.000Z	245	NTPC Renewable Energy Limited
Rajasthan	2027-03-01T00:00:00.000Z	2027-03-01T00:00:00.000Z	800	ReNew Solar Power Private Limited
Jharkhand	2026-07-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	310	Green Valley Renewable Energy
Gujarat	2028-01-01T00:00:00.000Z	2028-01-01T00:00:00.000Z	400	ReNew Solar Power Private Limited
Madhya Pradesh	2027-09-01T00:00:00.000Z	2027-09-01T00:00:00.000Z	200	ReNew Solar Power Private Limited
Karnataka	2026-09-27T00:00:00.000Z	2026-09-27T00:00:00.000Z	250	Clean Renewable Energy Hybrid Eight Private Limited (SPV of Hero Solar Energy Private Limited)
Gujarat	2026-04-04T00:00:00.000Z	2026-03-31T00:00:00.000Z	200	Avaada GJSolar Private Limited
Madhya Pradesh	2024-02-28T00:00:00.000Z	2025-06-30T00:00:00.000Z	120	NTPC Renewable Energy Limited
Jharkhand	2025-06-26T00:00:00.000Z	2025-06-26T00:00:00.000Z	8	Damodar Valley Corporation (DVC)

Karnataka	2025-04-01T00:00:00.000Z	2026-04-01T00:00:00.000Z	202.5	Tata Power Renewable Energy Limited
Gujarat	2025-09-30T00:00:00.000Z	2025-09-30T00:00:00.000Z	1200	Gujarat State Electricity Corporation Limited
Rajasthan	2025-03-31T00:00:00.000Z	2025-09-30T00:00:00.000Z	500	NTPC Renewable Energy Limited
Rajasthan/Karnataka/Andhra Pradesh	2025-06-28T00:00:00.000Z	2026-08-22T00:00:00.000Z	300	Project Nine Renewable Power Private Limited
Gujarat	2025-06-30T00:00:00.000Z	2026-02-28T00:00:00.000Z	180	NTPC Renewable Energy Limited
Rajasthan/Karnataka/Madhya Pradesh	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	400	ACME Venus Urja Private Limited
Gujarat	2025-08-20T00:00:00.000Z	2025-08-20T00:00:00.000Z	200	National Hydroelectric Power Corporation Limited
N.A.	2026-10-18T00:00:00.000Z	2026-10-18T00:00:00.000Z	700	JSW Renew Energy Eleven Limited
Rajasthan	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	1000	ReNew Solar (Shakti Six) Private Limited
Rajasthan	2026-05-01T00:00:00.000Z	2026-05-01T00:00:00.000Z	300	Hazel Hybren Private Limited
Karnataka	2026-09-27T00:00:00.000Z	2026-09-27T00:00:00.000Z	350	ACME Platinum Urja Private Limited
Rajasthan	2026-03-31T00:00:00.000Z	2026-03-31T00:00:00.000Z	500	NTPC Renewable Energy Limited
Rajasthan	2025-01-01T00:00:00.000Z	2025-12-31T00:00:00.000Z	100	Juniper Green Cosmic Private Limited
Maharashtra	2024-12-12T00:00:00.000Z		13.2	TP Surya Limited
Rajasthan	2026-12-30T00:00:00.000Z	2026-12-30T00:00:00.000Z	300	Auxo Sunlight Private Limited
Madhya Pradesh	2027-12-31T00:00:00.000Z	2027-12-31T00:00:00.000Z	700	Avaada KNClean Private Limited
Rajasthan	2026-02-28T00:00:00.000Z	2026-02-28T00:00:00.000Z	150	Saimaa Solar Private Limited
Karnataka	2024-10-31T00:00:00.000Z	2025-10-31T00:00:00.000Z	870	Tata Power Renewable Energy Limited
Gujarat	2024-04-30T00:00:00.000Z	2025-06-30T00:00:00.000Z	1255	NTPC Renewable Energy Limited

Additionally, after understanding the current progress and planned progress, a map illustrating the distribution of all the projects (619 power projects) across India, with a total installed capacity of 203,451.99 MW was done (*see Figure 2.3.*). It highlights operational projects (indicated by circles), projects in the pipeline (squares), and retired projects (lines). Additionally, it marks ISGS (Inter-State Generating Stations), rooftop, and ground-mounted solar installations (stars). The map demonstrates a wide distribution of projects across the country, with significant concentrations in states like Rajasthan, Gujarat, Maharashtra, Tamil Nadu, and the northeastern region, reflecting India's extensive efforts to diversify and expand its power infrastructure.

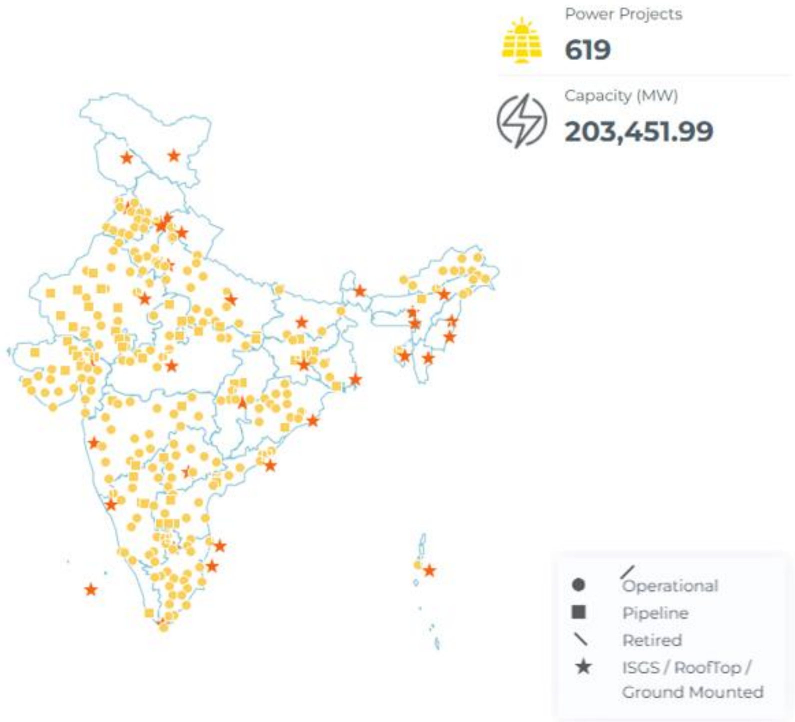


Figure 2.3. *Overall state level progress in solar photovoltaic installatons in India with count of projects and capacity (in MW) along with installaton variants adopted. (Source: MNRE's National Institute of Solar Energy, NPP-National Power Portal and CEA-Central Electricity Authority)*

These projects reflect the country's commitment to scaling up its renewable energy capacity to meet its ambitious targets of achieving 280 GW of solar energy by 2030, as part of the larger 450 GW renewable energy goal. This section highlights the key trends, capacities, and implementing agencies involved in the development of solar power projects, along with their anticipated commissioning timelines. The data indicates that numerous solar power projects are currently under construction across states such as Rajasthan, Gujarat, Maharashtra, Andhra Pradesh, Madhya Pradesh, West Bengal, and Karnataka. These projects showcase a diverse mix of stakeholders, including private firms, joint ventures, and public-sector entities like the National Thermal Power Corporation (NTPC) and the Solar Energy Corporation of India (SECI).

Key highlights of the pipeline include:

- Pipeline Capacity: As of December 2022, the total pipeline capacity of under-construction solar PV projects in India exceeds tens of thousands of megawatts, with Rajasthan alone accounting for a significant portion of this capacity. Rajasthan, being one of the sunniest states in India, has projects with capacities ranging from 50 MW to 2,000 MW, implemented by developers like Adani Renewable Energy, ReNew Solar Power, and Avaada Energy.
- Project Types and Scale: The projects include both large-scale utility solar parks and decentralized installations. For instance, Rajasthan and Gujarat are witnessing the implementation of mega solar parks with capacities over 1,000 MW, while smaller projects of 50–300 MW are being developed in states like

Maharashtra, Andhra Pradesh, and West Bengal. These variations in scale highlight India's strategy of balancing large-scale renewable energy hubs with smaller, decentralized energy solutions.

- Commissioning Timelines: The scheduled commissioning dates for these projects span from 2023 to 2030, illustrating a long-term roadmap for increasing solar energy capacity. However, many projects, such as those in Gujarat, Maharashtra, and Rajasthan, have anticipated delays in their commissioning timelines due to challenges like land acquisition, regulatory clearances, and supply chain disruptions.

Despite the ambitious pipeline of solar projects, several challenges hinder their timely implementation:

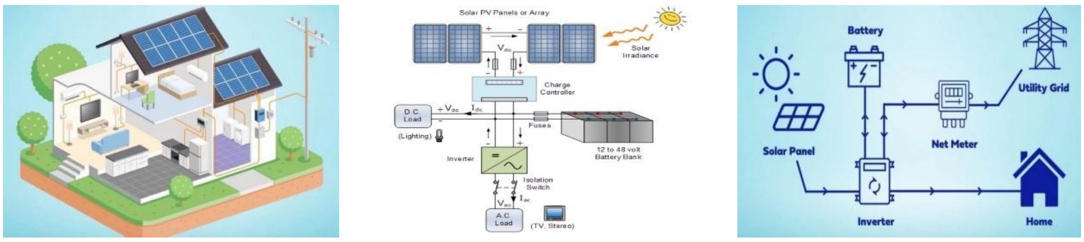
- Land Acquisition: Large-scale solar projects require significant land, leading to potential conflicts over land use and delays in approvals.
- Policy and Regulatory Hurdles: Variations in state-level policies, delays in tariff approvals, and bureaucratic inefficiencies often slow project progress.
- Grid Infrastructure: Integrating large-scale solar projects into the existing grid infrastructure is a challenge, particularly in remote areas where grid access is limited.

The extensive pipeline of solar projects underscores India's commitment to achieving its renewable energy targets and transitioning to a low-carbon energy system. These projects, when completed, will contribute significantly to:

- Energy Security: Reducing dependence on imported fossil fuels and diversifying India’s energy mix.
- Climate Goals: Supporting India’s commitments under the Paris Agreement by reducing greenhouse gas emissions.
- Economic Development: Creating jobs, fostering local industries, and driving rural electrification through decentralized applications.
- Sustainable Communities: Providing reliable, affordable, and clean energy solutions to underserved regions, enhancing the quality of life in rural areas.

2.3. Solar PV Systems Classification

Solar PV systems are generally classified as three main categories from an electric grid infrastructure point of view, see in *Figure 2.4*. They are grid-connected PV systems, standalone PV systems, and hybrid PV systems.



(a) (b) (c)

Figure 2.4. (a). Grid connected PV system; (b). Stand-alone model of solar PV system; (c). Hybrid solar PV *(Source: Chandrika et al., 2021)*

2.3.1. Grid Connected PV Systems

A grid-connected photovoltaic system, or grid-connected PV system, is a solar power system that is connected to the utility grid. This means that the solar PV system generates electricity from the sun and feeds it into the grid, where it can be used by the homeowner or business owner, or sold back to the utility company. In a grid-connected PV system, the solar panels generate DC (direct current) electricity, which is converted to AC (alternating current) electricity by an inverter. The AC electricity is then used to power the home or business, and any excess electricity is fed back into the grid. Grid-connected PV systems can generate more electricity than is required or used, especially during periods of high solar radiation such as in the long, hot summer months. This excess electricity can be stored in batteries for later use or fed back into the electrical grid. In a grid-connected PV system, the homeowner or business owner can use solar energy to power their energy needs during the day and draw power from the electrical mains grid at night or on cloudy days when solar energy production is reduced. This provides the best of both worlds, as it allows the user to take advantage of the clean and renewable energy provided by solar PV systems while still having access to reliable and consistent power from the electrical grid when needed. In a grid-connected PV system, electricity flows back and forth between the solar panels and the electrical mains grid based on the availability of sunshine and the current electrical demand. The PV solar panels are electrically connected or "tied" to the local mains power grid, allowing electrical energy to flow in both directions. Grid-connected PV systems are also known as "grid-tied" or "on-grid" solar systems. They can range in size from small rooftop systems for homes and businesses to large utility-scale solar power plants.

They have some issues such as with voltage regulation, compromising power quality, ferro resonance are few disadvantages of the system. However, they are known for their advantages which are as follows:

- Several system operators offer programmes like net metering and feed-in tariffs that can help users offset the cost of their electricity usage. Nevertheless, in some areas, grid technology are unable to handle distributed generation coming into the grid, making it impossible to export excess power, which must instead be earthed.
- Easy installation as they don't need a battery system.
- No storage losses involved, as this system provide the benefit of maximum usage of generated power.
- Average reduction in carbon consumption that is relatively predictable.

2.3.2. Stand Alone Solar System

An off-grid or stand-alone photovoltaics system typically consists of a number of individual photovoltaic modules or panels, each with a power output ranging from 50 to 100+ watts and typically rated at 12 volts. These PV modules are then combined into a single array to produce the desired output of power. Stand-alone PV systems are ideal for applications in isolated rural areas or where alternative power sources are either impractical or unavailable to supply power for lighting, appliances, and other uses. In these situations, a stand-alone PV system can provide a reliable and independent source of electricity. Stand-alone PV systems typically include a charge controller, battery bank, and inverter to store and convert the electricity generated by the solar panels. The charge controller regulates the flow of electricity to the battery bank to prevent overcharging or discharging, while the inverter converts the DC electricity stored in the battery bank to AC electricity for use by electrical appliances and devices.

2.3.3. Hybrid Solar PV system

A hybrid solar system is a combination of a grid-tied solar system and an off-grid solar system. It typically includes a battery backup to store excess electricity generated by the solar panels, allowing the system to provide power even when there is no sunlight or during power outages. The battery backup in a hybrid solar system can be charged by the solar panels or by the grid, depending on the system design and requirements. This flexibility allows the system to use the most cost-effective source of electricity at any given time. One of the most significant advantages of a hybrid solar system is its ability to provide uninterrupted power in the event of a power outage. When the grid goes down, the battery backup can provide power to critical loads, such as lighting, refrigeration, and communication devices, allowing you to continue to use electricity even when the grid is offline. There are different types of hybrid solar systems available, such as solar diesel, PV wind, and solar thermal.

2.4. Various installations and Configurations in Solar PV systems

There are many more PV configurations and designs available today, thanks to advancements in materials and technology. Some of these configurations are discussed in this section.

2.4.1. Open-mount photovoltaics

Utility-scale solar power plants with a large surface area are typically ground-mounted PV systems. The solar modules in the PV array are held in place by racks or frames that are fastened to mounting supports that are anchored to the ground. PV systems that are ground-mounted can be positioned with the best tilt and orientation.

Some ground-based mounting supports are:

- Ground Pole mounts, which are implanted in concrete or pushed into the ground.
- Concrete footings or concrete slabs for foundation mounts.
- Ballasted footing installations, which do not require ground penetration and employ weight to hold the solar module system in place, include concrete or steel bases.

These open mounted systems are used in residential as well as for commercial applications. Large solar parks are installed in many places utilizing the available free land. The idea of a "Solar Park" is to create a structure to facilitate the development of solar power generating projects in a concentrated region by giving developers access to a well-defined area and providing specialised infrastructure to lower infrastructure costs for each solar developer in the area. For solar parks, a sizable rack that holds the modules is positioned on the ground. In Rajasthan, India world’s largest solar park covering a total area of 5,700 hectares is located as of 2022 in Bhadla, Phalodi tehsil, Jodhpur district.

Figure 2.5. Ground installed PV plant (Source: Kumar, B. S., & Sudhakar, K. (2015))

The authors Kumar, B. S., & Sudhakar, K. (2015), explained about one of the largest solar power plants in Ramagundam, Telangana (10 MW capacity) stating that it receives the best average solar irradiation and temperature of 4.97 kw h/m2/day, roughly 27.3 ^{o} C respectively. The plant is adjusted for seasonally tilted, having an annual performance ratio (PR) of 86.12 % and 1.96 to 5.07 h/d of final yield. With a yearly energy production of 15,798.192 mwh, it has a CUF of 17.68 %. Using the retscreen Software, the primary goal of the simulation project by Singh, S., et al. (2022) to evaluate the financial feasibility analysis of 10 MWP grid-associated solar photovoltaic (PV) power plants in seven Indian cities, a detailed analysis needs to be conducted.

The authors provided with an illustration to choose advantageous locations for solar PV power plants based on financial viability metrics. That's interesting to know that Allahabad City is the most profitable location for a 10 MWP grid-associated solar photovoltaic (PV) power plant based on financial viability metrics. The values of 16,686 mwh of energy exported to the grid (EEG), US$ 20,896.30/year of electricity export revenue (EER), and 19545.9 tco2/year GHG emission reduction are quite impressive. Gorakhpur city is marked as the second-most beneficial site, while Varanasi city is the least profitable one. Due to the negative values of NPV and ALCS, Agra and Kanpur, were not deemed appropriate. The article (Padmavathi, K., & Daniel, S. A. (2013)) analyses the 3 MW grid-connected SPV plant performance in the state of Karnataka using monitored data. The plant produced 1372 kwh of energy annually on average per kwp of installed capacity. For two years of plant operation, inverter and grid failure losses are estimated and the PV plant output is monitored at 5 minutes interval for 5 years. For a 5 MWh plant, a real-time performance study and system validation are conducted by Sundaram, S., & Babu, J. S. C. (2015) located in Sivagangai district, Tamilnadu. The system under study has an absolute daily average capture and system loss of 0.384 h/d and 0.65 h/d respectively. The 5 MWh system measured yearly average energy generation is 24.17 MWh/day, which is reasonably near to the expected annual average, with retscreen is 24055.25 kwh/day.

The reason for degradation of PV modules which are field mounted is discussed by authors Dubey, R., et al (2017). The authors mentioned that the so-called "excellent" modules' average degradation rate is 1.33 %/year, which is greater than the manufacturer projections that are frequently used in financial calculations. The faster degradation rates are also due to more microcracks in the modules and packaging materials like encapsulant and back sheet and installations of rating less than 100 kwp capacity exhibit greater degradation than big systems, which may in part be a result of the owner not exercising sufficient due diligence during the procurement and installation phases. Goura, R. (2015) discussed the analysis of a 1 mwp grid connected ground mount PV pant owned by Andhra Pradesh power generation corporation.

2.4.2. Building Attached/Integrated photovoltaics (BAPV/BIPV)

Urban buildings are increasingly using solar photovoltaics in recent years. Photovoltaic power stations are structures that may use solar energy to produce power. To produce electricity, solar panels are incorporated into or attached to the building's roof or front. Building integrated photovoltaics (BIPV) and building applied photovoltaics (BAPV) are two categories of PV systems based on how they are installed and constructed in buildings (BAPV). Initially this section explains about BAPV systems followed by BIPV system.

Building-attached photovoltaic (BAPV) systems are solar power systems that are integrated into the building envelope, such as roofs, facades, or windows, to generate electricity. BAPV systems are becoming increasingly popular as they provide multiple benefits, such as reducing energy consumption, carbon emissions, and operating costs, while also enhancing building aesthetics and value. Building-attached photovoltaic (BAPV) systems combine the aesthetic appeal of a seamless integration into the overall building design with the economic and sustainability benefits of distributed solar energy generation. By integrating PV modules into the building envelope, BAPV systems can generate electricity where it is consumed, reducing the need for energy transmission and distribution infrastructure, and lowering carbon emissions. BAPV systems can also help to reduce energy consumption and costs, provide shading and insulation, and increase the value of the building. Additionally, BAPV systems can contribute to achieving green building certifications and help to meet regulatory requirements for renewable energy generation. Overall, BAPV systems are a great example of how renewable energy technology can be integrated into our built environment to create a more sustainable and efficient energy system. BAPV technology utilises additional mounting framework and movable rails to be fixed directly to the structures. The building structures and how they operate in this situation are not directly impacted by the system.

(a) (b)

Figure 2.6. (a). BAPV system; (b). BIPV systems (Source: Reddy, et al. (2020))

The study by Reddy, et al (2020) examined the BIPV/BAPV system's current state in India. The authors mentioned about the Indian solar mission, the targets of achieving GW of power by 2022, potential use of BAPV/BIPV in india. Building-integrated photovoltaics (BIPV) or building-applied photovoltaics (BAPV) can be installed on various parts of a building's envelope, including the roof and facades. The paper by Singh, D., Chaudhary, R., & Karthick, A. (2021) discusses a number of variables that have an impact on the BAPV/BIPV system applications' performance and design. The elements include window to wall ratio transmittance, cell coverage ratio, air gap, the rate ventilation, PV shading devices tilt angle, neighbouring shading, semi-transparent glazing design of PV, and orientation. The optimum cleaning frequencies caused by dust accumulation rates and the analysis of the impact of soiling specifically on rooftop building-applied photovoltaic (BAPV) systems is discussed in article Yadav, S. K., (2022), where the location is chosen in an Indian composite climatic region. The average daily dust deposition rate throughout the course of the year was 122 milligram/m^2/day. Spring saw 0.39 % soiling loss every day, with winter coming in second at 0.34 % per day. Due to high rainfall, the monsoon season had the lowest soiling loss, which was measured at 0.24 % per day. The integrated system of 25 kwp on Indian Institute of Technology, Delhi consists of a PV array on the roof of the building and a solar tracking system. The PV array is oriented towards the south with a tilt of 15° to maximize solar energy generation (Bansal, N. K., & Goel, S. (2000)). In order to protect the solar photovoltaic interior roof from the summer heat, a hybrid system of mechanical and natural ventilation and cooling systems is a system that combines both mechanical and natural methods of ventilation and cooling to optimize the building's energy efficiency and comfort is proposed.

The electrical and thermal performance of an existing grid-joined building integrated has been assessed by Ranjan, A., et al (2008) in five different cities. For evaluating thermal and electrical gain, fourteen distinct array combinations of PV integrated air ducts mounted on roofs have been taken into consideration and the system's overall electricity efficiency is found to be 9.64%. The research by Aaditya, G., Pillai, R., & Mani, M. (2013) examined the real-time performance evaluation of an installed 5.25 kwp BIPV system located at the Indian Institute of Science's, Center for Sustainable Technologies. 6 % was reported to be the overall average system efficiency for the time period May 2011–April 2012. The article by Pillai, D. S., Shabunko, V., & Krishna, A. (2022) gives a thorough description of the BIPV market, products, technology, and applications around the world. Also, this work undertakes a thorough review of 35 distinct BIPV outdoor test systems and the test results provided in literature given the significance of real-world testing and data analytics. Kumar, N. M., Sudhakar, K., & Samykano, M. (2019) in their research compared the performance of BAPV & BIPV (building integrated photo voltaic) system for a 32.7 kwp capacity. The different yield parameters and year-to-year energy production fluctuation of BAPV and BIPV technologies are found to vary from 1910 to 2100 kwh, respectively, and range from 43,700 to 46,800 kwh. The CUF and PR fluctuate between 15.25 % to 16.33 % and 72.23% to 77.36%, respectively.

2.4.3. Roof-mount / Roof integrated solar PV

Roof mount solar PV systems are a type of building-integrated photovoltaic (BIPV) system that involves installing solar panels directly onto the roof of a building. These systems are becoming increasingly popular due to their cost-effectiveness and ease of installation.

Here are some of the advantages and disadvantages of roof mount solar PV systems:

- Space efficiency: Installing solar panels on the roof can be a space-efficient solution for buildings with limited available land.
- Reduced energy bills: Roof mount solar PV systems can help to reduce energy bills by generating electricity that can be used to power the building.
- Increased property value: Installing a solar PV system can increase the value of the property and make it more attractive to potential buyers.

Figure 2.7. Rooftop solar PV system (Source: Satsangi, et al. (2019))

In the work Satsangi, K. P., et al (2019), the performance of a solar rooftop photovoltaic microgrid is given with notable attention on self-utilization and grid interconnection, in Indian setting. According to the findings, when corelate to comparable systems reported, with battery storage, the microgrid under study has the highest self-consumption at 89%. A roof-top photovoltaic plant of 5 kwp performance analysis was conducted, and the impact of temperature was examined by Yadav, S. K., & Bajpai, U. (2018). Reference yield(5.23 kwh/kwp/day) array yield(4.51

kwh/kwp/day), final yield(3.99 kwh/kwp/day), system (11.34 %), inverter (88.38 %) and array (10.02 %) efficiency were found on annual average daily basis. The annual average capacity utilisation factor was 16.39 %, while average daily performance ratio was 76.97 %. The plant's annual energy output was 7175.4 kwh. The real time performance of a 100 kwp rooftop solar PV system installed on an educational institute in north India is compared with a PV syst software.

The performance analysis of one megawatt rooftop solar plant is presented by Thotakura, S., (2020), which is installed on an educational institute in Andhra Pradesh. PV plant monitored data is collected for 12 months and the outputs are compared with three software tools (PVGIS, PV Watts and pvsyst). During the observation period, the solar PV plant supplied 1325.42 mwh of energy to the grid. The observations found that the mean bias error (MBE) was on average 5.33% (PVGIS), 12.33% (PV Watts), and 30.64% (PV Syst), while the normalised mean bias error (NMBE) was on average 2.954% (PVGIS), 7.88% (PV Watts), and 22.75% (PV Syst). At the same study location and on the 1 mwp plant the authors Navothna, B., & Thotakura, S. (2022) presented the degradation analysis. Light-induced deterioration is expected to result in an annual energy loss of 2.7 %, and module degradation rates range from 0.6 % to 5 %. The article Kumar, N. M., (2019) forecasts how a roof-integrated crystalline photovoltaic (PV) system of capacity 200 kw constructed at Complex-5, Chandigarh, Northern India, is functioning. The estimated outcomes indicate that the anticipated PV system is capable of producing 292.954 mwh of energy annually. The estimated annual CF, PR, and energy losses for the system are 16.72 %, 77.27 %, and 26.5 %, respectively. The PV system's predicted degradation rate would range from 0.6 to 5 %/year.

2.3.4. Solar photovoltaic tree

A structure called the Solar Power Tree is shaped like a tree and has steel branches that support solar panels. It uses biomimicry concepts to address a critical global issue by modelling a natural system—in this case, a tree. The centre pillar of the solar tree, which resembles a trunk, conducts electricity from the photovoltaic “leaves” that absorb sunlight to an internal battery. Many designs use rotatable panels that can move as the sun moves during the day to maximise solar absorption. Solar tree offers a variety of products that range in power from 1 kw to few kw. It requires little maintenance and is resilient in all-weather situations. Moreover, it requires 95% less ground space to install solar panels of the same capacity. From a single Solar Tree, 4 to 64 units of energy can be produced per day, ranging from 1 to 16 kw, can be networked together to produce more power. Compared to a conventional solar power plant, it rotates like a sunflower to provide 20 % more generation. Durgapur, West Bengal's Central Mechanical Engineering Research Institute (CMERI), has created the first Solar Power Tree in India. [https://www.cseindia.org/india-s-first-solar-power-tree-8032]. There are different configurations in the design of solar tree. The numerous types of designed trees on display include spiralling phyllotaxy solar trees (SPST), Fibonacci pattern solar trees (FPST), single trunk with branches, and three-axis symmetric design, ross love grove solar tree (RLST), basic solar tree, super trees, and smart palm tree. Typical solar tree shapes, structures, and patterns can be seen as modules on a genuine tree (Almadhhachi, M., Seres, I., & Farkas, I. (2022)).

Figure 2.8. Tree structured solar PV configurations. (Source: Gangwar et al., 2021)

Gangwar, P., Tripathi, R. P., and Singh, A. K. (2021) provide a comprehensive analysis of the different solar photovoltaic tree designs and applications that are already in use around the world. The energy, financial, and environmental performance of solar photovoltaic trees was also investigated in this paper. Solar photovoltaic tree structures occupy 1% more area than flat solar PV and increase efficiency by 10% to 15% by offering variable height and a creative design. The techno-economic analysis of solar tree based irrigation system in India environment is emphasised in the research article Kumar, R., et al (2022). The number of days needed for various horticulture crop cycles and various phases of growth for water requirements are the basis for the data gathering. A public corporation park in Paruthipattu, Chennai, India, is the location for the case study for their work by Anand, S. S., & Mookambika, B. A. (2022) to make a comprehensive report on solar tree and conventional designs. They analysed that the area needed for the solar tree installation was less than 20 sq ft, but the area needed for the ground-mounted solar panels was 4420 sq ft. Installing the solar tree took less time and money than installing solar panels.

2.3.5. Façade-integrated photovoltaics

Figure 2.9. Façade-integrated PV configuration (Source: Ahmad & Zia (2022))

Façade-integrated photovoltaics (FIPV) is a technology that involves integrating solar panels into the facade of a building. FIPV systems are designed to generate electricity by harnessing the energy of the sun and converting it into usable electricity. FIPV systems can be integrated into the facade of a building in various ways, including through the use of solar panels that are attached to the exterior of the building, or by embedding solar cells directly into the building materials such as glass, concrete or tiles. One of the benefits of FIPV systems is that they can be designed to blend in seamlessly with the architecture of the building, making them an aesthetically pleasing alternative to traditional solar panels that are often installed on rooftops. FIPV systems can also provide shading to the building, reducing the amount of heat that is absorbed into the building and potentially reducing cooling costs. In addition to their aesthetic benefits, FIPV systems can also provide significant energy savings and reduce the carbon footprint of the building. FIPV systems can generate electricity that can be used to power the building or can be fed back into the grid, potentially offsetting the building's energy consumption and reducing its reliance on traditional fossil fuels. Overall, FIPV systems are an innovative and sustainable solution that can help buildings generate their own electricity while also contributing to a cleaner and more sustainable energy future.

In the study Ahmad, M., & Zia, H. (2022), a design framework for a photovoltaic façade that would replace a typical building's skin is proposed. It has made an effort to resolve some of the obstacles and hindrances to the adoption of the technology. It looks into the development of a system for assessing the performance of the photovoltaic facade's envelope. The study by H. Radhi (2010) explores how the total energy of building integrated photovoltaic systems (bipv) employed as a wall cladding system in the UAE commercial sector. The results demonstrate that for the southern and western façades, the embodied energy pay-back period for solar systems in the UAE is between 12 and 13 years.

Xiang, C., & Matusiak, B. S. (2022) seeks to create a comprehensive architectural approach that supports FIPV's integrative design for residential structures. As a case study, balcony prototypes and position patterns for high-rises were proposed in Trondheim, Norway. Then a series of simulations were used to analyse daylight and solar radiation. The findings demonstrated that side balconies might offer the optimum performance in terms of interior daylight and energy harvesting, and that FIPV designs with partial railing regions of balcony in complementary were the most visually appreciated kind. The study offered a brand-new integrated design approach that, from an architectural standpoint, supports the FIPV application for high-height buildings with balconies and can balance performance in terms of façade aesthetics, interior daylight, and energy productivity. The current study by Attoye, D. E., Tabet Aoul, K. A., & Hassan, A. (2017) lists the customization parameters including customization category, level, and techniques, as well as related architectural potential, and evaluation of these effect of a building integrated photovoltaic façade configuration. The authors Le Nguyen, L. D., et al. (2019, July) examined the façade PV systems integrated into commercial buildings in Vietnam. In the article (Bröthaler, T., et al (2021)), the authors discussed about the "COOLSKIN" system, a completely integrated method of operating a heat pump for dynamically cooling a test room using electricity produced by facade-integrated photovoltaic modules.

2.3.6. Floating photovoltaics

Floating photovoltaics (FPV) is a technology that involves installing solar panels on floating platforms that are placed on bodies of water such as lakes, reservoirs, and even the ocean. The solar panels used in FPV systems are similar to those used in traditional photovoltaic systems, but they are designed to be more durable and resistant to water and weather. One of the benefits of FPV systems is that they can be installed in areas where there is limited land available for traditional solar panel installations. By installing solar panels on bodies of water, FPV systems can help to reduce land use and minimize the impact of solar installations on sensitive ecosystems. In addition, FPV systems can also provide other benefits such as reducing water evaporation and improving water quality. The shading provided by the solar panels can help to reduce the amount of water that is lost to evaporation, which is particularly important in areas that experience droughts or have limited water resources. The solar panels can also help to reduce the growth of algae in the water, which can improve water quality. FPV systems are becoming increasingly popular around the world, particularly in countries with large bodies of water and high solar radiation. They are also being used for a variety of applications, including providing electricity for remote communities, powering water treatment facilities, and generating electricity for industrial processes. Overall, FPV systems are a promising technology that can help to expand the use of solar energy and provide sustainable solutions for meeting our energy needs while minimizing environmental impacts.

Figure 2.10 . Floating solar configuration (Source: Sahu et al., 2016)

The Floating PV technology, its current state, and numerous design alternatives are all covered in detail in the study by Sahu, A., Yadav, N., & Sudhakar, K. (2016).

Various advantages compared to land and other installations, the environment profits of floating solar configurations are discussed in detail. The concept of solar PV installations above the water's surface is briefly introduced in this article by Kumar, N. M., Kanchikere, J., & Mallikarjun, P. (2018) as a fresh and popular idea. The potential advantages of Floatovoltaics were enumerated, and these include increased energy efficiency, decreased operating temperatures, mitigation of land use, and water management. The performance of a model FPV plant in an Indian reservoir examined is presented in the work by Ravichandran, N., Ravichandran, N., & Panneerselvam, B. (2021). The Mettur dam reservoir in Tamil Nadu, India, is a building that houses a hydroelectric power plant with a capacity of 150 MW.The results show that a tracking FPV system has a total CO2 reduction potential of 135 918.87 t CO2.

The feasibilty of constructing a 1 MW floating SPV plant at Kota's lake,Kishor Sagar and Kota Barrage in Rajasthan is demonstrated (Mittal, D., Saxena, B. K., & Rao, K. V. S. (2017, April)). According to the analysis, the 1 MW floating plant at the Kota Barrage could generate 18,38,519 kwh of electricity per year, reducing CO2 emissions by approximately 1,714 tonnes, and the floating plant at Kishore Sagar Lake could generate 18,58,959 kwh of electricity per year, reducing CO2 emissions by approximately 1,733 tonnes. The 1 MW FPV plant is used to study the energy yield of the tracking type in Gurfude, S. S., & Kulkarni, P. S. (2019, December) which is located at Ambazari Lake in Nagpur, India. The information on the city of Nagpur's monthly solar radiation is acquired by PV- Watts Calculator. The amount saved, the reduction in CO2 emissions, and the DC output are calculated using the MATLAB code. With 2-

axis tracking, the 1 MW FPV plant generates 23,62,076.129 kwh, 22,02,749.886 kwh with 1-axis tracking, and 18,71,229.186 kwh with fixed tilt equal to latitude.

When compared to a GSPV plant of the same capacity and location, the planned 10 kwp FSPV plant at Koyana Dam produces 4.08% more electricity per year. (Gurfude, S. S., & Kulkarni, P. S. (2019, December)). With this facility, the 111.7 tonnes of CO2 emissions will be decreased. A single-axis tracking FSPV system produces 18.57% more energy than a fixed mounted FSPV system. A stationary FSPV system gains 27.3% less energy than a two-axis tracking FSPV system in a similar manner. According to economic studies, the Levelized Cost of Electricity (LCOE) is 4.064 Rs/kwh with a 9.4-year payback period.

2.3.7 Vehicle attached / Vehicle integrated photovoltaics

The term “vehicle-integrated photovoltaics” (VIPV) reflects to the integration of PV modules into cars on the mechanical, electrical, and design-technical levels. For cars in particular, there are very high aesthetic standards for incorporation into the design. To prevent limiting the load capacity of utility vehicles (such as trucks and buses), very lightweight PV modules are required. Caravans and mobile houses, delivery bicycles, trams, trains, ships, aeroplanes, and drones are some domain application. The benefits include improved mileage, less strain on the energy grid and charging infrastructure as a result of electricity generation close to consumers, and lower electricity charging costs. The application of innovative materials and production processes in comparison to typical module constructions, the need for individualised manufacture, and the requirement for the maximum efficiency values relative to surface area are the obstacles.

Figure 2.11. Vehicle attached PV (Source: Dr. Roland Goslich, PV magazine International)

In the work by Nadimuthu, L. P. R., & Victor, K. (2021), an electrical auto-rickshaw driven by solar energy is designed for use in rural areas. Their research examined the performance of a solar-powered electrical autorickshaw and seeks to determine the best angle for solar module deployment. Additionally, the article seeks to determine how solar power generation and the best angle for vehicle speed affect performance and energy efficiency in order to achieve environmentally sustainable transportation. The overall design of a cutting-edge solar-assisted electric auto rickshaw is described in this study by Mulhall, P., et al. (2010). The performance of the suggested solar electric three-wheeler is intended to be on par with or better than that of the standard vehicle, but with a more creative and effective design. A rickshaw prototype is constructed, four system drive-train choices are discussed, and the

ADVISOR software is used to simulate and assess various configurations. Moreover, the software HOMER was used for optimised model of infrastructure architectures. This study (Kim, H., Ku, J., Kim, S. M., & Park, H. D. (2022)) demonstrates the feasibility of placing solar panels on fast trains to generate electricity in Korea's longest route , KTX-Sancheon Gyeongbu line, connecting Seoul and Busan. The annual energy predicted in that route is 122.15 mwh of electricity. A GIS-based technique is proposed to calculate the solar train's photovoltaic potential and solar irradiation.

2.3.8. Locomotive-mount photovoltaics

Locomotive-mount photovoltaics (LMPV) is a technology that involves installing solar panels on the roof of a locomotive or train carriage to generate electricity. The solar panels used in LMPV systems are typically made of lightweight and durable materials that can withstand the vibrations and harsh conditions associated with train travel. One of the benefits of LMPV systems is that they can provide a source of renewable energy to power on-board equipment, reducing the need for traditional fossil fuels and potentially lowering operating costs. This can be particularly useful for trains that travel long distances or operate in remote areas where access to traditional energy sources may be limited. LMPV systems can also help to reduce the carbon footprint of the train and contribute to a cleaner and more sustainable transportation system. By generating electricity from the sun, LMPV systems can help to reduce greenhouse gas emissions and other harmful pollutants associated with traditional fossil fuels. There are also some challenges associated with LMPV systems, such as the limited amount of space available on the roof of the train and the need to balance the weight of the solar panels with the weight of the train. However, these challenges can be overcome through careful design and engineering. Overall, LMPV systems are a promising technology that can help to reduce the environmental impact of trains and provide sustainable solutions for meeting our transportation needs. As the technology continues to develop, we may see more trains and locomotives solar powered.

Figure 2.12. Locomotive attached PV system (Source: Vasisht, et al. (2014))

To determine if it would be feasible to put standard photovoltaic (PV) modules atop train coaches, a research was conducted by Vasisht, M. S., et al (2014). Their research has demonstrated that the area of coach roof tops is more than enough to provide the necessary electricity for a non-A/C coach's electrical loads during the day, even in the winter. During two to three years, solar module installation costs would be recouped. The implementation of this plan would also result in a 239 T reduction in annual CO2 emissions. The authors work in 2017 presented the effectiveness of solar photovoltaic modules installed on the roof of an Indian Railways train. The main goal was to measure how much less diesel was being consumed by the end-on generation system, which supplies the electrical load for the new generation of coaches. By attaching a coach with two flexible solar photovoltaic panels to three well-known south Indian trains, it was possible to drive it at up to 120 km/h. The expected advantages of running solar rail carriages are based on the experimental findings. One solar rail coach is predicted to provide at least 18 kwh of power per day, saving 1700 litres of diesel annually.

2.3.9. Rail track integrated photovoltaics

Rail track integrated photovoltaics (RTIPV) is a technology that involves integrating solar panels directly into the railway tracks to generate electricity. The solar panels used in RTIPV systems are designed to be durable and resistant to the stresses of train travel, as well as the weather and other environmental factors. One of the main benefits of RTIPV systems is that they can generate electricity that can be used to power trains and other equipment, reducing the reliance on traditional fossil fuels and potentially lowering operating costs. This can be particularly useful for railways that operate in remote areas or that have limited access to traditional energy sources. RTIPV systems can also provide other benefits, such as reducing the carbon footprint of the railway and contributing to a cleaner and more sustainable transportation system. By generating electricity from the sun, RTIPV systems can help to reduce greenhouse gas emissions and other harmful pollutants associated with traditional fossil fuels. Another potential benefit of RTIPV systems is that they can provide shading to the railway tracks, reducing the amount of heat that is absorbed into the tracks and potentially extending their lifespan. This can help to reduce maintenance costs and improve the overall sustainability of the railway system. There are also some challenges associated with RTIPV systems, such as the need to balance the weight of the solar panels with the weight of the trains and the need to ensure that the solar panels do not interfere with the safe operation of the trains. However, these challenges can be addressed through careful design and engineering. Overall, RTIPV systems are a promising technology that can help to reduce the environmental impact of railways and provide sustainable solutions for meeting our transportation needs. As the technology continues to develop, we may see more railways incorporating RTIPV systems as a key component of their infrastructure. Ning, F., Ji, L., Ma, J., Jia, L., & Yu, Z. (2021) advised about using a three-in-one PV railway integrated network model that fully takes into account the grid, load situations, and solar energy network features. Their research demonstrated that an RPIS (railway PV integrated system) may essentially accomplish self-consistent energy consumption with the progressive development of PV and energy storage systems, providing environmental advantages and significant flexibility. The incorporation of trackside photovoltaic (PV) power into the Urban Rail Transit DC traction power supply system has been thoroughly studied in this research by Shen, X., Wei, H., & Wei, L. (2020).

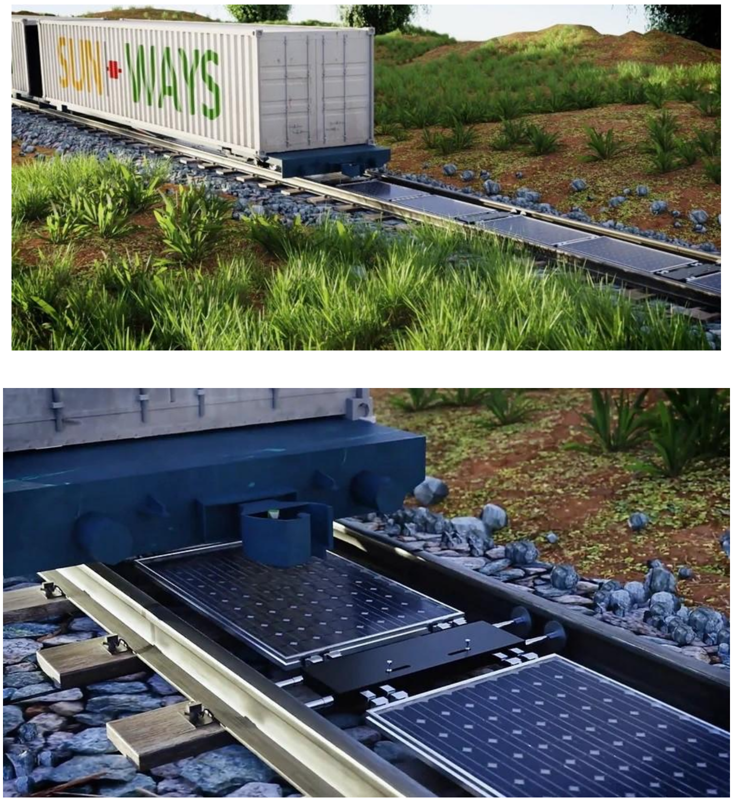


Figure 2.13. Rail track integrated PV configuration. (Source: Sun-Ways)

2.3.10. Submerged photovoltaics

Submerged photovoltaics is a technology that involves installing solar panels underwater, typically in bodies of water such as lakes, reservoirs, and the ocean. The solar panels used in submerged photovoltaics are designed to be durable and resistant to the harsh conditions associated with being submerged in water. One of the benefits of submerged photovoltaics is that it can generate electricity from a renewable source while minimizing land use and environmental impacts. In addition, submerged photovoltaics can also provide other benefits such as reducing water evaporation and improving water quality. By shading the water surface, submerged photovoltaics can help to reduce the amount of water that is lost to evaporation, which is particularly important in areas that experience droughts or have limited water resources. The solar panels can also help to reduce the growth of algae in the water, which can improve water quality. Another potential benefit of submerged photovoltaics is that it can provide a source of renewable energy in coastal areas where traditional land-based solar installations may not be feasible due to limited land availability or zoning restrictions. There are also some challenges associated with submerged photovoltaics, such as the need to ensure that the solar panels are securely anchored in place and the need to ensure that the underwater environment is not negatively impacted by the installation. However, these challenges can be addressed through careful design and engineering, as well as appropriate monitoring and maintenance. Overall, submerged photovoltaics is a promising technology that can help to expand the use of solar energy and provide sustainable solutions for meeting our energy needs while minimizing environmental impacts. As the technology continues to develop, we may see more underwater solar installations being used around the world.

A study is done by Rosa-Clot, et al. (2010) on the behaviour of a submerged photovoltaic (PV) panel. For single crystalline silicon panels, tests have been done. Findings are examined, and the efficiency gain is looked into and comprehended. The operational issues are examined, and advantages of installing underwater solar panels are highlighted.

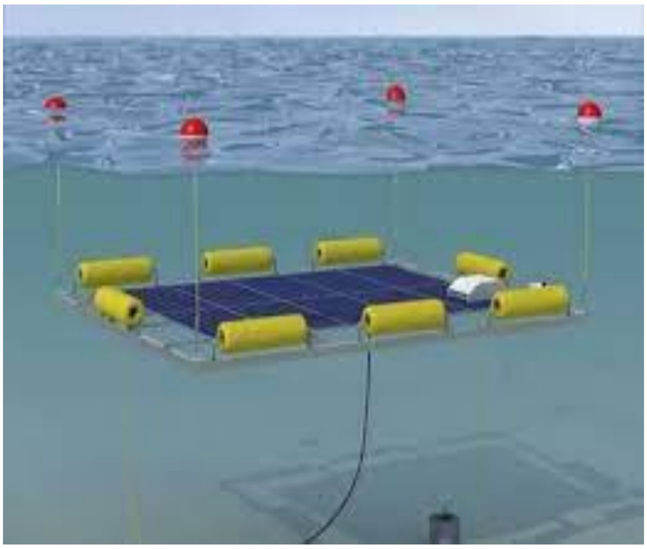


Figure 2.14. Water immersed PV systems (Source: Rosa-Clot, et al. (2010))

This article (Ajitha, A., et al (2019)) describes the experimental findings of the performance of amorphous silicon photovoltaic (TFPV) module's underwater. The electrical performance characteristics of a-Si TFPV are evaluated while taking the two installation circumstances for Submerged Photovoltaics (SPV) into account: shallow and deep oceans. Current, voltage, power input, power output, and power conversion efficiency are examples of electrical performance characteristics. It has been discovered that power outputs in deep seas are slightly lower than in shallow waters due to differences in incident sunlight on the photovoltaic (PV) module. In the study (Enaganti, P. K., et al (2019)), an experimental system that simulates an underwater setting has been created to check the performance of PV cell, giving because of changes in incident sunlight on the photovoltaic (PV) module, power outputs in deep seas are slightly lower than in shallow seas. In a controlled indoor environment, a comparison of underwater solar radiation and the performance of several silicon solar cells employing varied water conditions is made by Enaganti, P. K., & Goel, S. (2021). Underwater solar radiation propagation is examined as a function of water depth and various water conditions, such as when salts and minerals are dissolved in the water. The experiment's by Sheeba, K. N., Rao, R. M., & Jaisankar, S. (2015) show how a PV panel's many characteristics can vary in an underwater environment. The experiment's greatest efficiency averaged around 21.6%, which is impressive given the weather conditions under which it was conducted. The authors Röhr, J. A., et al (2020) proven that underwater solar cells can achieve efficiencies ranging from 55 % in shallow water to more than 65 % in deep water while maintaining a power density more than 5 mw cm-2, using detailed-balance calculations. Based on the environmental factors at the places of application, their results offer a guide for selecting the best underwater solar cell materials.

2.3.11. Pole-mounted photovoltaics

Pole ground mount is a particularly reliable option for demands involving small-scale photovoltaic solar power. It supports installations in a variety of places thanks to its manually adjustable 10 to 30-degree angle settings. The small on-grid or off-grid power station can be placed next to a water pump, mobile communications tower, exterior electrical house, or in a garden, farm, or mountain. The structure's angle can be manually changed to accommodate seasonal variations.

Figure 2.15. Pole Mount PV (Source: Primiceri & Visconti (2017))

Primiceri, P., & Visconti, P. (2017) exemplify and described the usage of modern IoT-based devices and recent technological advancements in solar-powered LED lighting systems in order to achieve energy savings, minimal maintenance costs, and the provision of extra services to users or the community. The authors conclude that the solar-powered LED-based lighting systems provide a great way for off-grid communities and locations to efficiently light up huge areas without relying on the power grid and by installing wireless modules, LED streetlights create a mesh communication network that collects and sends data to a central control unit in the cloud. This network is used to deliver relevant information to city personnel and to guarantee proper site management for police officers. The authors Ambhore, D. S., et al. (2020) looked into how factors like solar panel mounting angle, panel size, battery capacity, pole spacing, boom angle, etc effect the performance of streetlight systems. They mentioned that a dusk and dawn sensor will enable the use of LED lights at various intensities, reducing energy waste. Using the ideal boom angle and pole spacing will reduce blind spots and improve system performance.

2.3.12. Pole-integrated photovoltaics

The poles integrated with solar panels on its sides is the pole integrated PV configuration which are preferably used for street lightings. This model has an advantage of easy cleaning, less dust/snow formation, strong resistance to wind and compact structure.

Figure 2.16. Pole integrated PV system (Source: Ambhore et al. (2020))

2.3.13. Canopy-mounted solar photovoltaics

A canopy is an overhanging structure or an overhead roof to which a fabric or metal covering is fastened. It can offer shelter from weather conditions like the sun, snow, and rain. Solar PV attached to these canopies in parking lots for generating power, for electric charging etc. The amount of energy required to run your building can be decreased with a solar canopy. Your building may run on the power produced by the solar canopy during midday peak sunlight. When the amount of renewable energy generated is greater than what is now required, the excess energy is stored by your system for later use. There are two categories in this configuration: architectural solar canopy and fixed tilt solar canopy.

Figure 2.17. Solar Canopy (Source: Umer et al. (2019))

The authors Umer, F., et a (2019) using the online helioscope programme created by Folsom Labs, a thorough study has been conducted for the selection of solar parking sites, maximum solar energy output, and its capability effects with the shade of adjacent trees and structures. Their extensive economic research demonstrates that the installation of solar in car parking at the proposed location offset 14% of the cost of power while reducing energy consumption from the grid by 17% annually. Using several operational scenarios, the integration of a solar carport canopy to a future EV charging station is examined by Fakour, H., et al. (2023). The Kaohsiung municipal carport in southern Taiwan has undergone a thorough examination that covers electricity production, the effects of emissions, and the financial analysis of the solar EV charging station. A case study's findings revealed a possible solar energy yield of 140 MWh/year, which could power more than 3000 automobiles per month with 1 hour of parking time while emitting 94% less carbon dioxide overall than electricity generated using conventional grid methods.

2.3.14. Road-attached photovoltaics

Road-attached photovoltaics is a technology that involves installing solar panels on or adjacent to roadways to generate electricity. The solar panels used in road-attached photovoltaics are typically thin and flexible, allowing them to be integrated into various surfaces, including pavement, sidewalks, and noise barriers. One of the benefits of road-attached photovoltaics is that they can generate electricity while utilizing underutilized space such as roads and sidewalks. This can be particularly useful in urban areas where land is limited and expensive. In addition, road-attached photovoltaics can also provide other benefits such as reducing the urban heat island effect, improving air quality, and reducing noise pollution. Another potential benefit of road-attached photovoltaics is that they can provide a source of renewable energy for electric vehicles, enabling them to recharge while driving or parked on the road. This can help to expand the use of electric vehicles and reduce dependence on fossil fuels. There are also some challenges associated with road-attached photovoltaics, such as the need to ensure that the solar panels are durable enough to withstand heavy traffic and other environmental factors. In addition, the installation of road-attached photovoltaics can be more complicated than traditional solar installations due to the need to coordinate with local authorities and ensure that the installation meets safety standards. Overall, road-attached photovoltaics is a promising technology that can help to expand the use of solar energy and provide sustainable solutions for meeting our energy needs. As the technology continues to develop, we may see more roadways and sidewalks incorporating road-attached photovoltaics as a key component of their infrastructure. This technology is not yet tried in India but China and very few other countries started testing over these.

Figure 2.18. Road-attached photovoltaics. (Source: France's Tourouvre-au-Perche)

France's Tourouvre-au-Perche is one of the first solar-powered highways. Its covers 2,800 m^2, has a 420 kW maximum power production, and cost €5 million to install. This suggests that each installed kw will cost €11,905 (£10,624) [https://theconversation.com/solar-panels-replaced-tarmac-on-a-road-here-are-the-results-103568]. Because the road is planned to generate 800 kWh per day (kWh/day), some recently disclosed data suggests an output closer to 409 kWh/day, or 150,000 kWh/yr. The main reason is that solar panels are buried beneath a road has a lot of drawbacks. It will create less power and be more susceptible to shading since it is not tilted at the ideal angle, which is an issue because shading that covers just 5% of a panel's surface can cause a 50% reduction in power generation. Furthermore, the panels are likely covered in grit and filth, necessitating considerably thicker glass than typical panels to withstand the weight of traffic, reducing the amount of light they can absorb.

2.4. Review of Solar Policies in India

India has set ambitious targets for the development of solar energy in the country, and has several future plans in this regard. Some of the key future plans of India on solar energy are:

- Target of 450 GW by 2030: India has set a target of achieving a total installed capacity of 450 GW of renewable energy, including solar energy, by the year 2030. Of this, 280 GW is expected to come from solar energy alone.
- Development of Ultra-Mega Renewable Energy Parks: India plans to set up Ultra-Mega Renewable Energy Parks, each with a capacity of at least 2 GW, to accelerate the deployment of solar power in the country. The government has identified 50 potential sites for the parks across the country.
- Solarization of agriculture: India plans to promote the use of solar energy in the agriculture sector, through initiatives such as solar water pumps and solar-powered cold storage facilities. This will help to reduce the dependence of

farmers on fossil fuels and increase their income by reducing the cost of irrigation and storage.

- Development of floating solar power projects: India plans to develop floating solar power projects on large water bodies, such as reservoirs and dams, to increase the efficiency of land use and generate more electricity.
- Promotion of rooftop solar: India plans to promote the installation of rooftop solar panels on residential and commercial buildings, through incentives such as net metering, feed-in tariffs, and subsidies. The government has set a target of installing 40 GW of rooftop solar capacity by 2022.

Solar policies helps in promoting renewable energy, understanding opportunities, compliance, and planning for the future. By staying up-to-date with solar policies, individuals and businesses can make informed decisions about their investments in solar power and contribute to a more sustainable future. Understanding about solar policies is important for several reasons:

- Promoting renewable energy: Solar policies play a crucial role in promoting the use of renewable energy sources, such as solar power. By incentivizing the use of solar power through policies such as subsidies, tax credits, and feed-in tariffs, governments can encourage individuals and businesses to switch to cleaner and more sustainable energy sources.
- Understanding opportunities: By understanding the solar policies in a particular country or region, individuals and businesses can identify the opportunities that are available to them for investing in solar power. This can include incentives

for installing solar panels on residential or commercial properties, or opportunities to invest in large-scale solar power projects such as solar parks.

- Compliance: Solar policies often come with regulatory requirements that must be met by individuals and businesses that wish to take advantage of them. By knowing the details of the policies, individuals and businesses can ensure that they are in compliance with the relevant regulations.
- Planning for the future: Knowing about solar policies can help individuals and businesses to plan for the future, by identifying the likely trends in the solar power industry and the regulatory environment. This can help individuals and businesses to make informed decisions about their investments in solar power, and to develop long-term strategies for meeting their energy needs.

2.4.1. Key solar policies in India

Table 2.6, shows key policies. These policies and initiatives have helped to create a favourable environment for the growth of the solar industry in India. The country has become one of the world's largest solar energy markets, and is expected to continue to grow in the coming years.

Table 2.6. Key policies responsible for solar energy progress in India (Source: MNRE-Ministry of New and Renewable Energy and NITI Aayog)

Policy Name	**Brief Highlight**
Jawaharlal Nehru National Solar Mission (JNNSM)	Launched in 2010, JNNSM aims to promote the development and use of solar energy in the country. The mission has set a target of

	installing 100 GW of solar power by 2022, with a focus on grid-connected solar power projects.
National Solar Energy Federation of India (NSEFI)	NSEFI is a national association of solar energy stakeholders in India. It aims to create a platform for the promotion and development of solar energy in the country. NSEFI works with the government to develop policies and initiatives that support the growth of the solar industry
Solar Energy Corporation of India (SECI)	SECI is a government-owned company that facilitates the implementation of solar projects in the country. It acts as an intermediary between project developers and utilities, and also provides support for the development of solar parks.
Renewable Purchase Obligation (RPO)	RPO is a policy that mandates power utilities to purchase a certain percentage of their total power generation from renewable sources. The policy has helped to create a demand for solar power and has encouraged the development of solar projects in the country

Net Metering Policy	Net metering is a policy that allows solar power producers to sell excess power generated by their systems to the grid. The policy has helped to encourage the installation of rooftop solar systems in homes and businesses
Solar Parks	The government has set up solar parks in various parts of the country to facilitate the development of large-scale solar projects. The parks provide infrastructure such as land, transmission lines, and other facilities to project developers.

Jawaharlal Nehru National Solar Mission (JNNSM)

The Jawaharlal Nehru National Solar Mission (JNNSM) is a flagship program of the Indian government that was launched in 2010 with the goal of promoting the development and deployment of solar energy in the country. The mission aims to achieve an ambitious target of 100 GW of solar energy capacity by the year 2022.

The key objectives of the JNNSM are:

- To create an enabling policy framework for the deployment of solar energy in the country.
- To create favorable conditions for the development of solar manufacturing capability in the country.

- To promote research and development in the solar energy sector.
- To promote the use of solar energy in urban and rural areas.
- To create a conducive environment for the private sector to invest in the solar energy sector.

The JNNSM has two main components: grid-connected solar power and off-grid solar applications. Under the grid-connected component, the government provides various incentives such as financial support, tax exemptions, and subsidies to project developers to encourage the development of solar power projects. The off-grid component aims to promote the use of solar energy in areas that are not connected to the national grid. The JNNSM has also launched various initiatives to promote the development of solar energy in the country, such as the National Solar Mission Scheme, Solar City Programme, and Solar Rooftop Programme. The mission has also established a Solar Energy Corporation of India (SECI), which acts as an intermediary between project developers and utilities and facilitates the implementation of solar projects in the country.

In conclusion, the JNNSM has been instrumental in promoting the growth of the solar industry in India. The mission has created a conducive policy environment and provided financial support to project developers to encourage the deployment of solar energy in the country. The mission has also facilitated the development of solar manufacturing capability in the country, which has helped to create jobs and boost the economy.

National Solar Energy Federation of India (NSEFI)

The National Solar Energy Federation of India (NSEFI) is a non-profit organization that represents the interests of the Indian solar industry. The organization was formed in 2013 with the goal of promoting the development and deployment of solar energy in the country. The NSEFI has a wide range of members, including project developers, equipment manufacturers, financial institutions, and other stakeholders in the solar industry. The organization works closely with the government to develop policies and initiatives that support the growth of the solar industry. Some of the key objectives of the NSEFI are:

- To create a favourable environment for the growth of the solar industry in the country.
- To promote the development of solar manufacturing capability in the country.
- To promote research and development in the solar energy sector.
- To promote the use of solar energy in urban and rural areas.
- To provide a platform for networking and knowledge sharing among stakeholders in the solar industry.

The NSEFI has been instrumental in promoting the growth of the solar industry in India. The organization has worked closely with the government to develop policies and initiatives that support the deployment of solar energy in the country. The NSEFI has also helped to create a conducive environment for the private sector to invest in the solar industry, which has helped to boost the growth of the industry. The NSEFI has also launched various initiatives to promote the development of the solar industry in the country, such as the Solar Developer Meet, which brings together project developers and investors to discuss the latest trends and opportunities in the solar industry.

In conclusion, the NSEFI has been a key player in promoting the growth of the solar industry in India. The organization has provided a platform for stakeholders in the solar industry to come together and collaborate on initiatives that support the growth of the industry. The NSEFI's efforts have helped to create a favourable environment for the growth of the solar industry in the country, which has helped to reduce the country's dependence on fossil fuels and promote sustainable development.

Solar Energy Corporation of India (SECI)

The Solar Energy Corporation of India (SECI) is a public sector enterprise that was established under the administrative control of the Ministry of New and Renewable Energy (MNRE) in India in 2011. The main objective of SECI is to facilitate the implementation of the National Solar Mission and other solar programs in India. SECI is responsible for promoting, developing, and deploying solar energy in the country. The organization facilitates the implementation of solar projects through various activities such as site identification, selection of project developers, bidding, and contracting. SECI also provides financial assistance to solar projects, including incentives, subsidies, and soft loans. SECI has played a key role in promoting the growth of the solar industry in India by facilitating the implementation of large-scale solar projects. The organization has been responsible for implementing some of the largest solar projects in the country, such as the 750 MW Rewa Solar Park in Madhya Pradesh and the 1,000 MW Solar Park in Kurnool, Andhra Pradesh.

SECI has also played a vital role in promoting the use of solar energy in rural areas through its off-grid solar programs. The organization has implemented various initiatives to promote the use of solar energy in remote and rural areas, such as the Solar Pumping Programme, which promotes the use of solar pumps for irrigation in rural areas. In addition to its core activities, SECI is also involved in research and development activities in the solar energy sector. The organization collaborates with various research institutions and universities to promote research and development in solar energy and to develop new technologies for the sector. In conclusion, the Solar Energy Corporation of India (SECI) has been a key player in the growth of the solar industry in India. The organization has facilitated the implementation of large-scale solar projects and promoted the use of solar energy in rural areas. SECI's efforts have helped to reduce the country's dependence on fossil fuels and promote sustainable development.

Renewable Purchase Obligation (RPO)

The Renewable Purchase Obligation (RPO) is a regulatory mechanism that has been put in place by the Government of India to promote the use of renewable energy in the country. The RPO requires electricity distribution companies, captive power plants, and open-access consumers to purchase a certain percentage of their total electricity consumption from renewable energy sources. The RPO mechanism has been introduced to help India achieve its renewable energy targets under the National Solar

Mission and the National Wind Mission. The RPO requires obligated entities to purchase a specified percentage of their total electricity consumption from renewable energy sources, which is gradually increased over time. The current RPO targets in India are 18% for solar energy and 10% for wind energy by 2022. The obligated entities can meet their RPO targets through various means, such as generating renewable energy themselves, purchasing renewable energy from third-party generators, or purchasing Renewable Energy Certificates (recs). Recs are tradable certificates that represent the renewable energy generated by a power plant, and can be purchased by obligated entities to meet their RPO targets. The RPO mechanism has played a crucial role in promoting the growth of the renewable energy sector in India. The mechanism has created a demand for renewable energy, which has led to the development of new renewable energy projects and technologies. The RPO has also helped to reduce the country's dependence on fossil fuels and promote sustainable development. In conclusion, the Renewable Purchase Obligation (RPO) is a regulatory mechanism that has been put in place by the Government of India to promote the use of renewable energy in the country. The RPO requires obligated entities to purchase a certain percentage of their total electricity consumption from renewable energy sources.

Net Metering Policy

Net metering is a policy mechanism that allows consumers to generate their own electricity using renewable energy sources, such as solar panels or wind turbines, and to receive credit for any excess electricity that they generate and export to the grid. In India, the net metering policy has been introduced by the state governments to encourage the installation of rooftop solar panels on residential, commercial, and industrial buildings. The policy allows consumers to generate their own electricity using solar panels and to export any excess electricity back to the grid. Under the net metering policy, the electricity generated by the consumer's solar panel system is first used to meet the consumer's electricity demand. Any excess electricity that is generated and not used by the consumer is exported back to the grid, and the consumer receives credit for this exported electricity. This credit is deducted from the consumer's electricity bill, effectively reducing the amount of electricity that the consumer has to purchase from the grid. The net metering policy has been introduced in several states in India, including Delhi, Maharashtra, Tamil Nadu, and Karnataka. The policy has helped to promote the use of rooftop solar panels in the country, and has encouraged consumers to become more self-sufficient in meeting their energy needs. The policy has also helped to reduce the country's dependence on fossil fuels and promote sustainable development.

In conclusion, the net metering policy is a policy mechanism that has been introduced by the state governments in India to encourage the installation of rooftop solar panels. The policy allows consumers to generate their own electricity using solar panels and to receive credit for any excess electricity that they generate and export to the grid.

Solar Parks

Solar parks are large-scale solar power projects that are designed to generate a significant amount of electricity using solar panels. In India, solar parks have been introduced as a part of the country's efforts to increase its renewable energy capacity and meet its climate change commitments. Solar parks in India are typically large areas of land that are leased by the government to solar power project developers. The solar power developers then install solar panels on the land and generate electricity, which is sold to the grid. The electricity generated by the solar parks is used to meet the energy demand of the local area, and any excess electricity is exported to other parts of the country. The solar parks in India are managed by the Solar Energy Corporation of India (SECI), which is a government-owned company that is responsible for the development of large-scale solar power projects in the country. The solar parks in India have several advantages over small-scale solar power projects. Firstly, solar parks have economies of scale, which means that the cost of generating electricity is lower compared to small-scale solar power projects. Secondly, solar parks require less land per unit of electricity generated, making them a more efficient use of land. Thirdly, solar parks can be connected to the grid more easily, which means that the electricity generated can be used to meet the energy demand of a larger area. Solar parks are large-scale solar power projects that are designed to generate a significant amount of electricity using solar panels. In India, solar parks have been introduced to increase the country's renewable energy capacity and meet its climate change commitments.

2.4.2. Solar policies in different states in India:

The position of solar energy in each state of India varies, as each state has its own policies and programs related to the development of solar power. Here is a brief overview of the position of solar energy in some of the key states of India (see Table 2.7).

Table 2.7. Key policies at state level responsible for solar energy progress in individual states

State	Status of Solar Energy	Policies	Source
Karnataka	Karnataka is one of the leading states in India in terms of installed solar power capacity, with over 7 GW of installed solar power capacity as of 2021. The state has implemented several policies to promote solar power, including the Karnataka Solar Policy, 2014 and the Karnataka Solar Rooftop Policy, 2016.	-Karnataka Solar Policy, 2014 -Karnataka Solar Rooftop Policy, 2016.	(KERC, 2025)
Rajasthan	Rajasthan has abundant solar resources and has set a target of 30 GW of installed solar power capacity by 2025. The state has implemented several policies to promote solar power, including the Rajasthan Solar Energy Policy, 2019 and the Rajasthan Solar Park Policy, 2015.	-Rajasthan Solar Energy Policy, 2019 -Rajasthan Solar Park Policy, 2015.	(RERC, 2015)
Gujarat	Gujarat has been at the forefront of India's efforts to promote solar power, with over 4 GW of installed solar power capacity as of 2021. The state has implemented several policies to promote solar power, including the Gujarat Solar Power Policy, 2015 and the Gujarat Solar Rooftop Policy, 2016.	-Gujarat Solar Power Policy, 2015 -Gujarat Solar Rooftop Policy, 2016.	(GERC, 2025)
Tamil Nadu	Tamil Nadu has over 4 GW of installed solar power capacity as of 2021, making it one of the leading states in India in terms of installed solar power capacity. The state has implemented several policies to promote solar power, including the Tamil Nadu Solar Energy Policy, 2019 and the Tamil Nadu Solar Energy Policy, 2012.	-Tamil Nadu Solar Energy Policy, 2019 -Tamil Nadu Solar Energy Policy, 2012.	(TNERC, 2025)
Andhra Pradesh	Andhra Pradesh has set a target of 18 GW of installed solar power capacity by 2022 and has implemented several policies to promote	-Andhra Pradesh Solar Power	(APERC, 2025)

	solar power, including the Andhra Pradesh Solar Power Policy, 2018 and the Andhra Pradesh Solar Rooftop Policy, 2018.	Policy, 2018 -Andhra Pradesh Solar Rooftop Policy, 2018.	
Maharashtra	Maharashtra has over 3 GW of installed solar power capacity as of 2021 and has implemented several policies to promote solar power, including the Maharashtra Solar Energy Policy, 2017 and the Maharashtra Solar Rooftop Policy, 2018.	-Maharashtra Solar Energy Policy, 2017 -Maharashtra Solar Rooftop Policy, 2018.	(MHERC, 2025)
Uttar Pradesh	Uttar Pradesh has set a target of 10.7 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the Uttar Pradesh Solar Power Policy, 2017 and the Uttar Pradesh Solar Rooftop Power Policy, 2018. As of 2021, the state has over 2 GW of installed solar power capacity.	-Uttar Pradesh Solar Power Policy, 2017 -Uttar Pradesh Solar Rooftop Power Policy, 2018.	(UPERC, 2025)
Madhya Pradesh	Madhya Pradesh has set a target of 10 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the Madhya Pradesh Solar Policy, 2012 and the Madhya Pradesh Rooftop Solar Policy, 2016. As of 2021, the state has over 2 GW of installed solar power capacity.	-Madhya Pradesh Solar Policy, 2012 -Madhya Pradesh Rooftop Solar Policy, 2016	(MPERC, 2025)
Telangana	Telangana has set a target of 5 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the Telangana Solar Power Policy, 2015 and the Telangana Solar	-Telangana Solar Power Policy, 2015	(TGERC, 2025)

	Rooftop Policy, 2018. As of 2021, the state has over 3 GW of installed solar power capacity.	-Telangana Solar Rooftop Policy, 2018	
Kerala	Kerala has set a target of 1 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the Kerala Solar Energy Policy, 2013 and the Kerala Solar Rooftop Policy, 2019. As of 2021, the state has over 400 MW of installed solar power capacity.	-Kerala Solar Energy Policy, 2013 -Kerala Solar Rooftop Policy, 2019.	(KERC, 2025)
West Bengal	West Bengal has set a target of 1.5 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the West Bengal Solar Energy Policy, 2012 and the West Bengal Solar Rooftop Policy, 2019. As of 2021, the state has over 200 MW of installed solar power capacity.	-West Bengal Solar Energy Policy, 2012 -West Bengal Solar Rooftop Policy, 2019	(WBERC, 2025)
Odisha	Odisha has set a target of 1.5 GW of installed solar power capacity by 2022 and has implemented several policies to promote solar power, including the Odisha Solar Policy, 2013 and the Odisha Solar Rooftop Policy, 2016. As of 2021, the state has over 200 MW of installed solar power capacity	-Odisha Solar Policy, 2013 -Odisha Solar Rooftop Policy, 2016	(OERC, 2025)

Sources: *Karnataka State Electricity Regulatory Commission, RERC- Rajasthan Electricity Regulatory Commission, GERC-Gujarat Electricity Regulatory Commission, TNERC- Tamil Nadu Electricity Regulatory Commission, APERC- Andhra Pradesh Electricity Regulatory Commission, MHERC- Maharashtra Electricity Regulatory Commission, UPERC- Uttar Pradesh Electricity Regulatory Commission, MPERC- Madhya Pradesh Electricity Regulatory Commission, TGERC- Telangana Electricity Regulatory Commission, KERC- Kerala Electricity Regulatory Commission, WBERC- West Bengal Electricity Regulatory Commission, OERC-Odisha Electricity Regulatory Commission*

Each state in India has its own position on solar energy, with some states having higher installed solar power capacity than others. However, all states have implemented policies and programs to promote the development of solar power in their respective states.

Key features of Karnataka State Solar Policies:

Karnataka Solar Policy, 2014:

The Karnataka Solar Policy, 2014 was launched by the government of Karnataka to promote the development of solar power in the state. The policy aims to encourage the installation of solar power projects in Karnataka and achieve the target of 6 GW of installed solar power capacity by 2021.

Some of the key features of the Karnataka Solar Policy, 2014 are:

- Solar purchase obligation (SPO): The policy mandates that all electricity distribution companies (discoms) in the state must purchase a certain percentage of their total power procurement from solar power projects. The SPO for the discoms is set at 6% by 2021.
- Net metering: The policy encourages the installation of rooftop solar systems by allowing net metering. Under net metering, excess electricity generated by a rooftop solar system can be fed back into the grid and the consumer can receive credit for the excess energy supplied.
- Solar parks: The policy aims to set up solar parks in the state to promote the development of large-scale solar power projects. The policy provides incentives such as exemption from electricity duty, stamp duty, and registration fees for solar park developers.
- Renewable energy certificate (REC): The policy allows solar power project developers to earn recs for the electricity generated by their projects. These recs

can be traded on the power exchange and can provide an additional source of revenue for the solar power project developers.

- Incentives: The policy provides several incentives for solar power projects, including a waiver of electricity duty, exemption from wheeling and transmission charges, and priority access to the grid.

Karnataka Solar Rooftop Policy, 2016:

The Karnataka Solar Rooftop Policy, 2016 was launched by the Government of Karnataka to promote the installation of rooftop solar systems in the state. The policy aims to achieve a target of 400 MW of installed rooftop solar capacity by 2021. Here are some of the key features of the policy:

- Net metering: The policy allows for net metering for all rooftop solar systems with a capacity of up to 1 MW. The excess electricity generated by the system can be fed back into the grid, and the consumer can receive credit for the excess energy supplied.
- Subsidy: The policy provides a subsidy of up to 40% of the cost of the rooftop solar system, with a maximum limit of INR 20,000 per KW for residential consumers and INR 10,000 per KW for commercial consumers.
- Banking facility: The policy allows for banking of excess solar energy generated by the rooftop solar system for a period of up to one year. The consumer can use the banked energy during periods of low solar generation.

- Third-party ownership: The policy allows for third-party ownership of rooftop solar systems, enabling consumers to lease their rooftops to developers who can install, operate and maintain the solar systems.
- Grid connectivity: The policy mandates that all discoms in the state must provide grid connectivity for rooftop solar systems within 30 days of receiving an application.
- Incentives: The policy provides incentives for the installation of rooftop solar systems, such as exemption from electricity duty and wheeling charges, priority in net metering, and fast-track approval process for projects below 100 kw capacity.

Key features of Rajasthan State Solar Policies:

Rajasthan Solar Energy Policy, 2019:

The Rajasthan Solar Energy Policy, 2019 was launched by the Government of Rajasthan to promote the development of solar energy in the state. The policy aims to achieve a target of 30 GW of installed solar power capacity by 2024-25. Here are some of the key features of the policy:

- Solar purchase obligation (SPO): The policy mandates that all discoms in the state must purchase a certain percentage of their total power procurement from solar power projects. The SPO for the discoms is set at 10% by 2024-25.
- Net metering: The policy encourages the installation of rooftop solar systems by allowing net metering. Under net metering, excess electricity generated by a

rooftop solar system can be fed back into the grid and the consumer can receive credit for the excess energy supplied.

- Solar parks: The policy aims to set up solar parks in the state to promote the development of large-scale solar power projects. The policy provides incentives such as exemption from electricity duty, stamp duty, and registration fees for solar park developers.
- Hybrid parks: The policy encourages the development of hybrid parks that integrate solar power with wind or other renewable energy sources.
- Incentives: The policy provides several incentives for solar power projects, including a waiver of transmission and wheeling charges, exemption from electricity duty, and priority access to the grid.
- Capacity building: The policy aims to promote capacity building in the solar energy sector by providing training programs for engineers, technicians, and other stakeholders.

Rajasthan Solar Park Policy, 2015:

The Rajasthan Solar Park Policy, 2015 was launched by the Government of Rajasthan to promote the development of solar power parks in the state. The policy aims to facilitate the setting up of large-scale solar power projects in the state. Here are some of the key features of the policy:

- Land acquisition: The policy provides for the acquisition of land for solar power parks by the Rajasthan Renewable Energy Corporation Limited (RRECL), the nodal agency for the implementation of the policy. The RRECL can acquire land through purchase, lease, or direct acquisition.

- Facilitation of power purchase agreements (ppas): The policy aims to facilitate the signing of ppas between the solar power park developers and the discoms in the state. The RRECL will assist in the negotiation and signing of ppas.
- Connectivity to the grid: The policy mandates that all solar power parks must be connected to the grid through a dedicated transmission line. The RRECL will facilitate the connection of solar power parks to the grid.
- Incentives: The policy provides several incentives for solar power park developers, including exemption from electricity duty, stamp duty, and registration fees. The policy also provides a waiver of transmission and wheeling charges for solar power parks.
- Infrastructure support: The policy provides for the development of infrastructure such as roads, water supply, and other amenities required for the setting up of solar power parks.
- Monitoring and evaluation: The policy mandates the monitoring and evaluation of the solar power parks by the RRECL to ensure their timely completion and efficient operation.

Key features of Gujarat State Solar Policies:

Gujarat Solar Power Policy, 2015:

The Gujarat Solar Power Policy, 2015 was launched by the Government of Gujarat to promote the development of solar power in the state. The policy aims to achieve a target of 8,024 MW of installed solar power capacity by 2022. Here are some of the key features of the policy:

- Solar purchase obligation (SPO): The policy mandates that all discoms in the state must purchase a certain percentage of their total power procurement from solar power projects. The SPO for the discoms is set at 4% by 2021-22.
- Net metering: The policy encourages the installation of rooftop solar systems by allowing net metering. Under net metering, excess electricity generated by a rooftop solar system can be fed back into the grid and the consumer can receive credit for the excess energy supplied.
- Solar parks: The policy aims to set up solar parks in the state to promote the development of large-scale solar power projects. The policy provides incentives such as exemption from electricity duty, stamp duty, and registration fees for solar park developers.
- Incentives: The policy provides several incentives for solar power projects, including a waiver of transmission and wheeling charges, exemption from electricity duty, and priority access to the grid.
- Capacity building: The policy aims to promote capacity building in the solar energy sector by providing training programs for engineers, technicians, and other stakeholders.

Gujarat Solar Rooftop Policy, 2016:

The Gujarat Solar Rooftop Policy, 2016, is a government initiative aimed at promoting the adoption of solar power in the state of Gujarat, India. The policy was introduced to encourage the installation of solar rooftop systems on residential, commercial, and industrial buildings. The key objectives of the policy are to reduce the carbon footprint of the state, promote renewable energy, and create new job opportunities in the solar sector. The policy provides various incentives to individuals and organizations for the installation of rooftop solar systems. The policy aims to achieve a target of 3,200 MW of solar power generation through rooftop solar systems by the year 2022.

Under the policy, rooftop solar system owners are eligible for net metering, which means excess solar energy generated by the system can be fed back to the grid and the owner receives a credit for the energy supplied. The policy also provides for the purchase of surplus energy by the distribution companies at a predetermined rate. The Gujarat government has set up a nodal agency called Gujarat Energy Development Agency (GEDA) to implement the policy. GEDA provides technical support, facilitates the installation of solar systems, and provides information and guidance to the public.

Key features of Tamil Nadu State Solar Policies:

Tamil Nadu Solar Energy Policy, 2019:

The Tamil Nadu Solar Energy Policy, 2019 is a comprehensive policy framework developed by the Government of Tamil Nadu to promote the development of solar energy in the state. The policy aims to achieve a total installed solar power capacity of 9,000 MW by the year 2022. The policy also aims to encourage the development of the local solar industry and create new job opportunities in the sector.

The key features of the Tamil Nadu Solar Energy Policy, 2019 are as follows:

- Solar power generation targets: The policy aims to achieve a total installed solar power capacity of 9,000 MW by the year 2022. This includes both utility-scale solar projects and rooftop solar installations.
- Incentives for solar power: The policy provides incentives for solar power producers, including the provision of net metering, the exemption of electricity tax, and the waiver of certain transmission and wheeling charges.
- Solar parks: The policy provides for the development of solar parks in the state, with a focus on promoting the domestic solar industry. The policy encourages the development of a solar park exclusively for domestic manufacturing of solar components and equipment.
- Community solar projects: The policy encourages the installation of solar systems on common properties such as schools, hospitals, and community centers, which is expected to increase access to solar energy for communities.
- Research and development: The policy provides for the establishment of a research and development fund to support research in the solar sector.
- Monitoring and evaluation: The policy provides for the establishment of a monitoring and evaluation mechanism to track the progress of the solar energy sector in the state.

Tamil Nadu Solar Energy Policy, 2012:

Tamil Nadu Solar Energy Policy, 2012, was a policy framework developed by the Government of Tamil Nadu to promote the development of solar energy in the state. The policy aimed to increase the share of solar energy in the state's energy mix and promote sustainable energy practices.

The key features of the Tamil Nadu Solar Energy Policy, 2012, were as follows:

- Solar power generation targets: The policy aimed to achieve a total installed solar power capacity of 3,000 MW by the year 2015, with a focus on promoting both utility-scale solar projects and rooftop solar installations.
- Incentives for solar power: The policy provided incentives for solar power producers, including the provision of net metering, the exemption of electricity tax, and the waiver of certain transmission and wheeling charges.
- Solar parks: The policy provided for the development of solar parks in the state, with a focus on promoting the growth of the solar industry.
- Research and development: The policy provided for the establishment of a research and development fund to support research in the solar sector.
- Monitoring and evaluation: The policy provided for the establishment of a monitoring and evaluation mechanism to track the progress of the solar energy sector in the state.

Key features of Andhra Pradesh State Solar Policies:

Andhra Pradesh Solar Power Policy, 2018:

The Andhra Pradesh Solar Power Policy, 2018, is a policy framework developed by the Government of Andhra Pradesh to promote the development of solar energy in the state. The policy aims to increase the share of solar energy in the state's energy mix and promote sustainable energy practices.

The key features of the Andhra Pradesh Solar Power Policy, 2018, are as follows:

- Solar power generation targets: The policy aims to achieve a total installed solar power capacity of 5,000 MW by the year 2024, with a focus on promoting both utility-scale solar projects and rooftop solar installations.
- Incentives for solar power: The policy provides incentives for solar power producers, including the provision of net metering, the exemption of electricity tax, and the waiver of certain transmission and wheeling charges.
- Solar parks: The policy provides for the development of solar parks in the state, with a focus on promoting the growth of the solar industry. The policy also provides for the development of a Green Energy Corridor for the evacuation of solar power from remote areas to the grid.
- Community solar projects: The policy encourages the installation of solar systems on common properties such as schools, hospitals, and community centers, which is expected to increase access to solar energy for communities.
- Research and development: The policy provides for the establishment of a research and development fund to support research in the solar sector.

- Monitoring and evaluation: The policy provides for the establishment of a monitoring and evaluation mechanism to track the progress of the solar energy sector in the state.

Andhra Pradesh Solar Rooftop Policy,2018:

The Andhra Pradesh Solar Rooftop Policy, 2018 is a policy framework developed by the Government of Andhra Pradesh to promote the development of solar energy through rooftop solar installations in the state. The policy aims to increase the share of solar energy in the state's energy mix, reduce dependency on fossil fuels, and promote sustainable energy practices.

The key features of the Andhra Pradesh Solar Rooftop Policy, 2018, are as follows:

- Solar rooftop generation targets: The policy aims to achieve a total installed solar rooftop capacity of 500 MW by the year 2022.
- Incentives for solar rooftop: The policy provides incentives for solar rooftop installations, including the provision of net metering, the exemption of electricity tax, and the waiver of certain transmission and wheeling charges.
- Capital subsidies: The policy provides for capital subsidies to encourage the adoption of rooftop solar systems. These subsidies vary depending on the capacity of the system and the type of consumer.
- Grid connectivity: The policy mandates that all rooftop solar installations must be grid-connected to ensure that excess solar energy generated can be fed back into the grid.

- Community solar projects: The policy encourages the installation of solar systems on common properties such as schools, hospitals, and community centers, which is expected to increase access to solar energy for communities.
- Monitoring and evaluation: The policy provides for the establishment of a monitoring and evaluation mechanism to track the progress of the solar rooftop sector in the state.

Key features of Maharashtra State Solar Policies:

Maharashtra Solar Energy Policy, 2017:

The Maharashtra Solar Energy Policy, 2017 is a policy framework developed by the Government of Maharashtra to promote the development of solar energy in the state. The policy aims to increase the share of solar energy in the state's energy mix, reduce dependency on fossil fuels, and promote sustainable energy practices.

The key features of the Maharashtra Solar Energy Policy, 2017, are as follows:

- Solar power generation targets: The policy aims to achieve a total installed solar power capacity of 7,500 MW by the year 2022, with a focus on promoting both utility-scale solar projects and rooftop solar installations.
- Incentives for solar power: The policy provides incentives for solar power producers, including the provision of net metering, the exemption of electricity duty, and the waiver of certain transmission and wheeling charges.

- Solar parks: The policy provides for the development of solar parks in the state, with a focus on promoting the growth of the solar industry. The policy also provides for the development of a Green Energy Corridor for the evacuation of solar power from remote areas to the grid.
- Off-grid solar systems: The policy encourages the installation of off-grid solar systems in areas that are not connected to the grid, to provide electricity to these areas.
- Solar water pumps: The policy provides for the promotion of solar-powered water pumps to help farmers and rural communities access reliable and affordable energy for irrigation and other agricultural activities.

Maharashtra Solar Rooftop Policy, 2018:

The Maharashtra Solar Rooftop Policy, 2018 is a policy framework developed by the Government of Maharashtra to promote the installation of solar power systems on rooftops in the state. The policy aims to increase the share of solar energy in the state's energy mix, reduce dependency on fossil fuels, and promote sustainable energy practices.

The key features of the Maharashtra Solar Rooftop Policy, 2018, are as follows:

- Solar rooftop generation targets: The policy aims to achieve a total installed solar rooftop capacity of 2,000 MW by the year 2022.

- Incentives for solar rooftop: The policy provides incentives for solar rooftop installations, including the provision of net metering, the exemption of electricity duty, and the waiver of certain transmission and wheeling charges.
- Capital subsidies: The policy provides for capital subsidies to encourage the adoption of rooftop solar systems. These subsidies vary depending on the capacity of the system and the type of consumer.
- Grid connectivity: The policy mandates that all rooftop solar installations must be grid-connected to ensure that excess solar energy generated can be fed back into the grid.
- Community solar projects: The policy encourages the installation of solar systems on common properties such as schools, hospitals, and community centres, which is expected to increase access to solar energy for communities.

Several states in India have strong solar policies and have been promoting the development of solar energy in their respective regions. However, it is difficult to identify a single state with the strongest solar policy, as each state has its own unique policy framework and targets. Some of the leading states in India in terms of solar energy deployment include Rajasthan, Gujarat, Tamil Nadu, Karnataka, and Andhra Pradesh. These states have implemented a range of policy measures to promote the growth of the solar industry, including providing subsidies and incentives for solar energy development, setting up dedicated solar parks, and mandating the use of solar energy in certain sectors.

India has set ambitious targets for solar energy development, with a goal to achieve 100 GW of solar power capacity by the year 2022. While there have been challenges and delays in achieving these targets, there is still significant potential for India to achieve its solar policies. India has a favourable climate for solar energy development, with high solar irradiance in many parts of the country. Additionally, the Indian government has implemented various policy measures and incentives to promote the growth of the solar industry, including capital subsidies, tax exemptions, and net metering. However, achieving these targets will require significant investments in the solar sector, including the development of infrastructure, grid integration, and financing. The government has been working towards addressing these challenges by implementing regulatory frameworks and attracting private sector investments. The solar sector in India has already seen significant growth in recent years, with the country ranking among the top five global solar markets. With continued support from the government and private sector investments, India has the potential to achieve its solar policies and become a global leader in solar energy.

India has made significant progress in promoting the development of solar energy in recent years. The Indian government has set ambitious targets for solar power capacity, and several states have implemented strong policy frameworks to promote the growth of the solar industry. The policies implemented by the central and state governments provide various incentives and subsidies for solar energy development, including net metering, capital subsidies, and tax exemptions. Additionally, the government has set up dedicated solar parks, implemented regulatory frameworks to promote the adoption of solar energy, and established monitoring and evaluation mechanisms to track progress. These policy measures have contributed to the significant growth of the solar industry in India, making it one of the leading solar markets in the world. However, there are still challenges to overcome, including the need for better infrastructure and grid integration, as well as the availability of financing for solar projects. Overall, India's solar policies demonstrate a strong commitment to the growth of renewable energy and have the potential to contribute significantly to the country's energy security, while also promoting sustainable development and reducing carbon emissions.

2.5. Review of Feed-in Tariffs for solar power plants in India

It is important to know about Feed-in Tariffs (fits) for solar power plants because they are a key policy mechanism for promoting the development of renewable energy sources, such as solar power. Fits provide a guaranteed price for electricity generated by renewable sources, which can make it more attractive for developers to invest in renewable energy projects. In the case of solar power, fits have played a significant role in driving the growth of the solar industry in many countries, including India. By providing a stable and predictable revenue stream for solar power projects, fits have encouraged investment in solar power and helped to reduce the cost of generating solar power. In addition, fits have other benefits, such as reducing greenhouse gas emissions and improving energy security by diversifying the energy mix. Fits can also create local jobs in the renewable energy sector and can provide economic benefits to communities by reducing the amount of money spent on imported fossil fuels. Understanding fits for solar power plants can help individuals, businesses, and policymakers to make informed decisions about investing in renewable energy projects. It can also help to promote a more sustainable and low-carbon energy future, which is essential for addressing climate change and ensuring long-term energy security.

A Feed-in Tariff (fit) is a policy mechanism that offers a guaranteed price for electricity generated by renewable energy sources, such as solar power plants. In India, fits have played a significant role in promoting the development of solar power projects. The fit policy for solar power plants in India was first introduced in 2010 by the National Tariff Policy (NTP) of the Central Electricity Regulatory Commission (CERC). The policy was revised in 2015 and again in 2020 to reflect the changing market conditions and the costs of generating solar power. Under the fit policy, solar power project developers are paid a fixed tariff per unit of electricity generated, which is guaranteed for a fixed period of time, usually between 25 to 30 years. The fit rates are based on various factors, including the location of the project, the technology used, and the capacity of the project. In India, the fit rates for solar power projects vary depending on the state and the capacity of the project. For instance, in 2021, the fit rates for solar power projects in the state of Maharashtra ranged from INR 2.38 per kwh for projects up to 1 MW capacity to INR 2.82 per kwh for projects over 10 MW capacity. The fit policy has been instrumental in driving the growth of solar power in India, with the country now among the top solar markets in the world. The policy has attracted a significant amount of investment in solar power projects, and has helped to reduce the cost of solar power generation in India. Overall, the fit policy for solar power plants in India has been a successful mechanism for promoting renewable energy and reducing the country's dependence on fossil fuels. The policy is likely to continue to play a significant role in India's efforts to transition to a clean and sustainable energy future.

2.5.1. Key components in Feed-in tariffs for solar power plants in India

Feed-in tariffs for solar power plants in India are determined by a number of factors, including:

- Solar resource potential: fits take into account the solar resource potential of a particular location, which determines the amount of energy that can be generated by the solar power plant.
- Capital costs: The cost of building and operating a solar power plant is a key factor in determining fits. This includes the cost of solar panels, inverters, mounting structures, and other equipment.
- Operation and maintenance costs: fits also consider the ongoing costs of operating and maintaining a solar power plant, such as cleaning, repairs, and replacement of equipment.
- Financing costs: The cost of financing the construction of a solar power plant, including interest payments and other fees, is another key factor in determining fits.
- Grid integration costs: fits may also consider the cost of integrating solar power into the electrical grid, including the cost of building transmission lines, substations, and other infrastructure.

- Government incentives: Government incentives, such as tax credits and subsidies, can play a role in determining fits.
- Market conditions: fits are also influenced by market conditions, such as the cost of competing sources of energy and the demand for electricity.

2.5.2. Equation to calculate the fit for a solar power plant

The feed-in tariff (fit) for a solar power plant is typically determined by the relevant regulatory body or utility company in a given region or country. In India, fits are typically set by state electricity regulatory commissions. The equation used to calculate the fit for a solar power plant may vary depending on factors such as the capacity of the plant, the technology used, and the prevailing market conditions. The fit is expressed in terms of the price per kh that the utility or grid operator will pay the solar power plant owner for the electricity generated by the plant and fed into the grid. It's important to note that the formula used to calculate fit can vary based on the specific regulatory framework in each state or region, and other factors may also be taken into account when setting fits, such as the cost of grid integration, inflation, and risk factors. However, a general formula for calculating the fit for a solar power plant is:

$$FiT = \text{Total Project Cost} - \text{ Debt Component Expected Lifetime Generation x Capacity Utilization Factor x 1000}$$

Where:

Total Project Cost is the total cost of setting up and commissioning the solar power plant, including capital expenditures such as land, equipment, and installation costs; *Debt Component* is the proportion of the total project cost that is financed through debt; *Expected Lifetime Generation* is the estimated total electricity generation over the expected lifetime of the plant, in units of kilowatt-hours (kwh); *Capacity Utilization Factor (CUF)* is a measure of how efficiently the plant is expected to operate over its lifetime, expressed as a percentage.

2.5.3. Feed-in tariffs for different solar power projects

Feed-in tariffs for solar power projects may vary depending on the size, type, and technology used in the project. Here are some examples of fits for different types of solar power projects in India:

- Rooftop solar: Rooftop solar installations are typically smaller in scale and installed on residential or commercial buildings. Fits for rooftop solar projects in India may range from around Rs. 3.50 to Rs. 8.00 per kwh, depending on the state and other factors.
- Utility-scale solar: Utility-scale solar projects are typically larger in scale and installed on land, and may range from a few megawatts (MW) to several hundred MW in size. Fits for utility-scale solar projects in India may range from around Rs. 2.44 to Rs. 7.01 per kwh, depending on the state and other factors.
- Floating solar: Floating solar projects are installed on bodies of water such as lakes, reservoirs, or canals. Fits for floating solar projects in India may range

from around Rs. 3.00 to Rs. 7.00 per kwh, depending on the state and other factors.

- Hybrid solar: Hybrid solar projects combine solar PV with other sources of energy such as wind, hydro, or diesel generators. Fits for hybrid solar projects in India may vary depending on the specific technology used and the state.
- Solar with energy storage: Solar projects with energy storage systems (ESS) are becoming increasingly popular in India, as they can help to address issues such as intermittency and grid stability. Fits for solar projects with ESS may vary depending on the state and other factors.

2.5.4. Reasons for the variations in Feed-in tariffs between states in India:

Each state in India may have a different feed-in tariff for solar power plants due to a variety of factors. Some of the key reasons for the variation in fits between states include:

- Solar potential: Different states in India have different levels of solar irradiation, which affects the potential output and economics of solar power plants. States with higher levels of solar radiation may offer higher fits to encourage investment in solar power projects.
- Development goals: Each state has its own renewable energy development goals and may offer fits that align with these objectives. Some states may be more focused on achieving a certain level of installed solar capacity or reducing their carbon footprint, while others may prioritize energy security or job creation.

- Regulatory environment: State electricity regulatory commissions (sercs) are responsible for setting fits for solar power plants, and the regulatory framework can vary between states. Sercs may take different factors into account when setting fits, such as the cost of grid integration, inflation, and risk factors.
- Market conditions: fits may also be influenced by the prevailing market conditions in each state, such as the cost of electricity, the availability of financing, and the level of competition in the solar power market.
- Political factors: Political factors may also play a role in setting fits, as policymakers may have different priorities and agendas in different states.

2.5.5. Feed-in tariffs for Utility-scale solar power projects in various states of India

The feed-in tariffs for solar power plants in India vary by state and by the size and type of the solar power plant. The feed-in tariffs of each state in India are presented in the Table 4. The feed-in tariffs values change over the time as per the policies and regulations of each state. Also, the fits are different for various solar power projects such as rooftop solar installations versus utility-scale solar power plants.

Table 2.8: State-wise Feed-in Tariff for utility scale solar projects in India

State	**Feed-in tariff in Rs./kWh**	**Capacity**	**Source**
Andhra Pradesh	3.50	Up to 1 MW	(APERC- Andhra Pradesh Electricity Regulatory Commission, 2025)
Bihar	4.21	Up to 10 MW	(BERC- Bihar Electricity Regulatory Commission, 2025)
Chhattisgarh	3.40	Up to 5 MW	(CERC-Chhattisgarh Electricity Regulatory Commission, 2025)
Gujarat	2.25	Up to 4 MW	(GERC-Gujarat Electricity Regulatory Commission, 2025)

Haryana	4.50	Up to 1 MW	(HERC-Haryana Electricity Regulatory Commission, 2025)
Jharkhand	5.50	Up to 10 MW	(JERC-Jharkhand Electricity Regulatory Commission, 2025)
Karnataka	7.08	Up to 1 MW	(KSERC- Karnataka State Electricity Regulatory Commission, 2025)
Kerala	3.90	Up to 1 MW	(KERC-Kerala Electricity Regulatory Commission, 2025)
Madhya Pradesh	2.97	Up to 5 MW	(MPERC- Madhya Pradesh Electricity Regulatory Commission, 2025)
Maharashtra	3.25	Up to 1 MW	(MHERC-Maharashtra Electricity Regulatory Commission, 2025)
Meghalaya	4.50	Up to 1 MW	(MERC-Meghalaya Electricity Regulatory Commission, 2025)
Odisha	3.94	Up to 1 MW	(OERC-Odisha Electricity Regulatory Commission, 2025)
Punjab	5.13	Up to 1 MW	(PERC-Punjab Electricity Regulatory Commission, 2025)
Rajasthan	3.14	Up to 5 MW	(RERC-Rajasthan Electricity Regulatory Commission, 2025)
Tamil Nadu	2.60	Up to 1 MW	(TNERC-Tamil Nadu Electricity Regulatory Commission, 2025)
Telangana	6.50	Up to 1 MW	(TGERC-Telangana Electricity Regulatory Commission, 2025)
Tripura	3.50	Up to 1 MW	(TERC-Tripura Electricity Regulatory Commission, 2025)
Uttar Pradesh	6.02	Up to 2 MW	(UPERC-Uttar Pradesh Electricity Regulatory Commission, 2025)
Uttarakhand	3.10	Up to 1 MW	(UTERC-Uttarakhand Electricity Regulatory Commission, 2025)
West Bengal	6.07	Up to 1 MW	(WBERC- West Bengal Electricity Regulatory Commission, 2025)

Note: a consolidated report of FiT is available on MNRE-Ministry of New and Renewable Energy Portal at https://mnre.gov.in/en/

2.5.6. Feed-in tariffs for Rooftop solar power projects in various states of India

The Feed-in Tariffs for rooftop solar power projects in India may vary based on various factors, some of which include:

- Installed capacity: The fits may vary based on the size of the rooftop solar power project. Typically, smaller projects may receive higher fits than larger projects.
- Type of consumer: The fits may also vary based on the type of consumer. For instance, industrial or commercial consumers may receive different fits than residential consumers.

- Location: The fits may vary based on the location of the rooftop solar power project. Some states or regions may offer higher fits than others due to factors such as solar irradiation, grid availability, and government policies.
- Technology used: The fits may also vary based on the technology used for the rooftop solar power project. For example, projects that use more efficient solar panels or inverters may receive higher fits than those using less efficient technology.
- Project ownership: The fits may vary based on the ownership of the rooftop solar power project. Projects owned by individuals or small businesses may receive different fits than those owned by larger companies or utilities.

The Feed-in tariffs for Rooftop solar power projects in various states of India are as follows:

Table 2.9: State-wise Feed-in Tariff for roof-top solar projects in India

State	**Feed-in tariff in Rs./kWh**	**Source**
Andhra Pradesh	2.60 - 4.75	(APERC- Andhra Pradesh Electricity Regulatory Commission, 2025)
Bihar	4.00 - 5.50	(BERC- Bihar Electricity Regulatory Commission, 2025)
Chhattisgarh	2.75 - 4.00	(CERC-Chhattisgarh Electricity Regulatory Commission, 2025)
Delhi	2.00 - 4.00	(Joint Electricity Regulatory Commission for the State of Goa and Union Territories, 2025)
Goa	2.25 - 3.50	(Joint Electricity Regulatory Commission for the State of Goa and Union Territories, 2025)
Gujarat	1.75 - 3.00	(GERC-Gujarat Electricity Regulatory Commission, 2025)
Haryana	2.44 - 4.00	(HERC-Haryana Electricity Regulatory Commission, 2025)
Himachal Pradesh	2.00 - 4.50	(HPERC-Himachal Pradesh Electricity Regulatory Commission, 2025)
Jharkhand	5.50	(JERC-Jharkhand Electricity Regulatory Commission, 2025)

Karnataka	3.56 - 9.56	(KSERC- Karnataka State Electricity Regulatory Commission, 2025)
Kerala	2.50 - 4.00	(KERC-Kerala Electricity Regulatory Commission, 2025)
Madhya Pradesh	3.00 - 3.25	(MPERC- Madhya Pradesh Electricity Regulatory Commission, 2025)
Maharashtra	2.50 - 3.75	(MHERC-Maharashtra Electricity Regulatory Commission, 2025)
Manipur	5.50	(MERC-Manipur State Electricity Regulatory Commission, 2025)
Meghalaya	3.50 - 5.00	(MSERC-Meghalaya State Electricity Regulatory Commission, 2025)
Mizoram	5.00	(MERC-Mizoram Electricity Regulatory Commission, 2025)
Nagaland	5.00	(NERC-Nagaland Electricity Regulatory Commission, 2025)
Odisha	2.91 - 4.07	(OERC-Odisha Electricity Regulatory Commission, 2025)
Puducherry	3.40 - 5.60	(Joint Electricity Regulatory Commission for the State of Goa and Union Territories, 2025)
Punjab	3.40 - 6.00	(PERC-Rajasthan Electricity Regulatory Commission, 2025)
Rajasthan	3.93 - 6.30	(RERC-Rajasthan Electricity Regulatory Commission, 2025)
Tamil Nadu	2.60 - 4.50	(TNERC-Tamil Nadu Electricity Regulatory Commission, 2025)
Telangana	3.00 - 5.00	(TGERC-Telangana Electricity Regulatory Commission, 2025)
Tripura	3.50 - 4.50	(TERC-Tripura Electricity Regulatory Commission, 2025)
Uttar Pradesh	3.30 - 6.00	(UPERC-Uttar Pradesh Electricity Regulatory Commission, 2025)
Uttarakhand	2.90 - 3.40	(UTERC-Uttarakhand Electricity Regulatory Commission, 2025)
West Bengal	4.00 - 6.00	(WBERC- West Bengal Electricity Regulatory Commission, 2025)

Note: a consolidated report of FiT is available on MNRE-Ministry of New and Renewable Energy Portal at https://mnre.gov.in/en/

2.5.7. Feed-in tariffs (fits) for floating solar power projects in various states of India

The Feed-in Tariff (fit) for floating solar power projects in India can vary based on a range of factors, including:

- Solar irradiation levels: The amount of solar energy available at a specific location can influence the fit, as areas with higher solar irradiation may require a lower fit to make a project financially viable.
- Project capacity: Larger projects may require a lower fit, as they can benefit from economies of scale and lower per-unit costs.

- Location: Projects located in areas with higher land or water lease rates, or in areas with higher installation or maintenance costs, may require a higher fit.
- Technology used: Projects that use newer or more advanced technologies may require a higher fit to make the project financially viable.
- Government policies: fits may be influenced by government policies such as tax incentives, subsidies, or other forms of financial support that may be available to floating solar power projects.
- Competition: The fit may also be influenced by the level of competition in the market, with more competitive markets potentially leading to lower fits.

It's important to note that these factors may vary depending on the specific state or region in India where the floating solar power project is being developed. The Feed-in Tariffs (fits) for floating solar power projects in India vary across different states and are subject to change. Here are the fits for floating solar power projects in some of the states in India as of September 2021.

Table 2.10: State-wise Feed-in Tariff for floating solar projects in India

State	**Feed-in tariff in Rs./kwh**	**Source**
Andhra Pradesh	3.10	(APERC- Andhra Pradesh Electricity Regulatory Commission, 2025)
Assam	3.14	(AERC-Assam Electricity Regulatory Commission, 2025)
Bihar	3.14	(BERC- Bihar Electricity Regulatory Commission, 2025)

Chhattisgarh	3.20	(CERC-Chhattisgarh Electricity Regulatory Commission, 2025)
Goa	2.52	(Joint Electricity Regulatory Commission for the State of Goa and Union Territories, 2025)
Gujarat	3.00 to 3.22	(GERC-Gujarat Electricity Regulatory Commission, 2025)
Haryana	3.14	(HERC-Haryana Electricity Regulatory Commission, 2025)
Himachal Pradesh	3.27	(HPERC-Himachal Pradesh Electricity Regulatory Commission, 2025)
Jharkhand	3.00 to 3.15	(JERC-Jharkhand Electricity Regulatory Commission, 2025)
Karnataka	3.14	(KSERC-Karnataka State Electricity Regulatory Commission, 2025)
Kerala	3.14	(KERC-Kerala Electricity Regulatory Commission, 2025)
Madhya Pradesh	2.71 to 3.08	(MPERC-Madhya Pradesh Electricity Regulatory Commission, 2025)
Maharashtra	3.19	(MHERC-Maharashtra Electricity Regulatory Commission, 2025)
Meghalaya	3.14	(MSERC-Meghalaya State Electricity Regulatory Commission, 2025)
Mizoram	3.14	(MERC-Mizoram Electricity Regulatory Commission, 2025)
Manipur	3.14	(MERC-Manipur State Electricity Regulatory Commission, 2025)
Nagaland	3.14	(NERC-Nagaland Electricity Regulatory Commission, 2025)
Odisha	3.50	(OERC-Odisha Electricity Regulatory Commission, 2025)
Punjab	3.14	(PERC-Rajasthan Electricity Regulatory Commission, 2025)
Rajasthan	3.14	(RERC-Rajasthan Electricity Regulatory Commission, 2025)
Tamil Nadu	3.11	(TNERC-Tamil Nadu Electricity Regulatory Commission, 2025)
Telangana	3.14	(TGERC-Telangana Electricity Regulatory Commission, 2025)
Tripura	3.14	(TERC-Tripura Electricity Regulatory Commission, 2025)
Uttar Pradesh	3.35	(UPERC-Uttar Pradesh Electricity Regulatory Commission, 2025)
Uttarakhand	3.14	(UTERC-Uttarakhand Electricity Regulatory Commission, 2025)
West Bengal	3.15	(WBERC- West Bengal Electricity Regulatory Commission, 2025)

Note: a consolidated report of FiT is available on MNRE-Ministry of New and Renewable Energy Portal at https://mnre.gov.in/en/

In conclusion, Feed-in Tariff (fit) is an important policy tool that has helped India achieve significant growth in its solar power sector. Fits provide a guaranteed price for solar power developers, which helps to mitigate risks and ensure financial viability for solar projects. India has implemented fit programs for different types of solar power projects, including rooftop, utility-scale, and floating solar power projects, with varying fit rates based on factors such as location, technology used, and government policies. Fits have been instrumental in promoting the development of renewable energy in India and helping the country achieve its ambitious renewable energy targets. However, the fit rates are subject to change based on various factors, and it's important for developers to stay updated on the latest policies and regulations. Overall, fits have been a key driver in India's journey towards a more sustainable and renewable energy future, and they continue to play a critical role in promoting the growth of solar power projects in the country.

CHAPTER 3

RESEARCH GAPS, METHODOLOGY, AND FRAMEWORK

Building upon a comprehensive review of existing literature, this chapter identifies critical research gaps concerning the strategic adoption and deployment of photovoltaic (PV) power plant variants in India's electricity sector. Followed by explored research gaps, PV case studies were developed and analysed further with mixed methods approaches. Later a framework is proposed to mainly understand how sustainble communities can be created and what is the role of energy in it and how solar PV installation variants can promote it.

3.1. Research Gaps

The strategic adoption of photovoltaic (PV) power plant installation variants in India's electricity sector holds immense potential to advance sustainable development, energy security, and climate goals. This section outlines the key gaps identified through a comprehensive review of the literature, emphasizing areas where further investigation is essential.

Research Gap – 1: Comparative Analysis of Installation Variants

India's solar energy landscape includes utility-scale solar parks, rooftop solar systems, and decentralized off-grid installations. However, there is a lack of comparative studies analyzing the technical, economic, and environmental trade-offs among these installation variants. Their specific contributions to sustainability, grid efficiency, and energy access remain underexplored. Understanding the contextual suitability of each variant is crucial for their strategic adoption in India's diverse geographic and socio-economic settings.

Research Gap – 2: Integration with Grid Infrastructure

The rapid growth of solar energy in India has exposed challenges related to the integration of PV power plants into the country's existing grid infrastructure. The intermittent nature of solar power, coupled with aging grid systems, threatens grid stability and reliability. While energy storage systems and smart grid technologies are recognized as potential solutions, little research has been conducted on their cost-effectiveness, scalability, and applicability to India's electricity sector.

Research Gap – 3: **Environmental Assessments**

Although solar energy is considered environmentally friendly, the adoption of PV power plants raises several environmental challenges that require further exploration:

- Life Cycle Impacts: A comprehensive life cycle assessment (LCA) of PV systems—including their carbon footprint, water usage, and material resource extraction—is missing in the Indian context.
- Land Use and Biodiversity: Utility-scale solar parks often require large tracts of land, leading to potential conflicts with agricultural activities, forest areas, and biodiversity hotspots. Research on sustainable land-use planning and its ecological impacts is limited.

- Waste Management: The lack of effective recycling technologies and policies for decommissioned PV modules poses a risk of significant electronic waste accumulation.
- Cumulative Impacts: Large-scale solar installations concentrated in specific regions may have cumulative environmental effects, including changes to local microclimates, water resource depletion, and ecosystem disruptions, which have not been systematically analyzed.

Research Gap – 4: **Socio-Economic Impacts**

While the environmental benefits of PV power plants are well-documented, their socio-economic impacts remain insufficiently explored. Research on how PV installations contribute to rural electrification, job creation, and income generation is limited, particularly for marginalized and underserved communities. These impacts are critical for ensuring that PV adoption aligns with the broader goal of creating sustainable communities.

Research Gap – 5: **Policy and Regulatory Frameworks**

India's solar energy policies, including feed-in tariffs, net metering, and renewable purchase obligations (RPOs), have been instrumental in driving adoption. However, inconsistencies across state-level policies and regulatory barriers create uncertainties for investors and developers. Additionally, the effectiveness of these policies in addressing challenges like grid integration, financing, and land acquisition has not been adequately studied.

***Research Gap – 6:* Financing and Investment Models**

The high upfront costs of PV installations remain a significant barrier to widespread adoption. Although government subsidies and incentives have played a role in reducing this barrier, there is limited research on innovative financing mechanisms—such as green bonds, crowdfunding, and public-private partnerships—that could attract investments and make solar energy more accessible to small-scale adopters.

***Research Gap – 7:* Regional Disparities**

The adoption of PV power plants varies significantly across India's states and union territories due to differences in solar potential, policy support, and land availability. These regional disparities have not been adequately analyzed, particularly in terms of how they impact equitable access to renewable energy and the socio-economic benefits of solar adoption.

***Research Gap – 8:* Climate Resilience and Performance**

India's diverse climatic conditions—ranging from extreme heat and dust storms to heavy monsoons—affect the performance, efficiency, and maintenance of PV systems. Research on climate-resilient materials, designs, and technologies that can optimize PV systems for long-term performance in India's varied climatic zones is lacking.

3.2. Case study design and Mixed methods approach for analysis

As per the literature explored solar power plant installation variants (*see Figure 3.1.* for consolidated variants), system design is conceptulised considering three types of PV system designs as shown in *Figure 2.3* of the chapter 2 in section 2.1.

Figure 3.1. *Installation variants in photovoltaics power plants. (Used With Permission Kumar et al., 2020). SPVT = solar photovoltaic tree; OMPV = open-mount photovoltaics; RMPV = roof-mount photovoltaics; BAPV = building attached photovoltaics; CMSPV = canopy-mounted solar photovoltaics; RIPV = roof-integrated photovoltaics; FIPV = façade-integrated photovoltaics; BIPV = building-integrated photovoltaics; VAPV = vehicle attached photovoltaics; VIPV = vehicle-integrated photovoltaics; RoAPV = road-attached photovoltaics; RoIPV = road-integrated photovoltaics; LoMPV = locomotive-mount photovoltaics; RaTIPV = rail track integrated photovoltaics; FPV = floating photovoltaics or floatovoltaics; FSPV = floating solar photovoltaics; SPV = submerged photovoltaics; UobSPV = underwater on-board solar photovoltaics; PMPV = pole mounted-photovoltaics; PIPV = pole-integrated photovoltaics.*

3.2.1. Performance modelling using standarised metrics

Performance parameters of the solar PV system include final yield (Y_F), system efficiency η, performance ratio (PR) and capacity factor (CF), as defined by IEC 61724:1998 standard and in accordance to the Photovoltaic Power Systems Programme (PVPS) of the International Energy Agency (IEA) (IEC61724, 1998, IEA-PVPS, 2014, Woyte et al., 2014).

The final yield Y_F is the relation between the electrical energy injected into the grid (E_{AC}) by the solar PV plant and the installed nominal power (P_{rated}), as given by:

$$Y_F = \frac{E_{AC}[kWh]}{P_{rated}[kW]} \quad [h]. \tag{3.1}$$

The system efficiency η is expressed as the ratio of the electrical energy supplied to the power grid (E_{AC}) and the solar energy (H_{POA}), incident on the surface of the total modules (A). It is computed as:

$$\eta = \frac{E_{AC}[kWh]}{H_{POA}[kWh/m^2]*A[m^2]}*100 \quad [\%]. \tag{3.2}$$

The performance ratio (PR) represents the ratio between the actual energy generated by the PV plant and the energy generated by the ideal PV without losses in the same conditions of the solar irradiance, as follows:

$$PR = \frac{Y_F}{Y_R}*100 \quad [\%]. \tag{3.3}$$

The PR is one of the foremost parameters to assess the overall efficiency of PV systems, enabling the benchmarking of grid-connected PV systems of any power anywhere in the world.

The reference yield (Y_R) is the total solar energy on the plane of array (H_{POA}) related to the reference irradiance (G_{STC}) (1000 W/m^2) at standard test conditions (STC), as given:

$$Y_R = \frac{H_{POA}\,[\frac{kWh}{m^2}]}{G_{STC}\,[kW/m^2]} \quad [h]. \tag{3.4}$$

The capacity utilization factor (CF) expresses the ratio of the real annual electrical energy and the electrical energy that could be generated in the nominal power condition operating 24 hours a day. The capacity factor is determined by:

$$CF = \frac{E_{AC}[kWh]}{P_{rated}[kW] * 8760[h]} * 100 \quad [\%]. \tag{3.5}$$

It is possible to refer to daily and monthly yield, efficiency, and performance ratio of the PV system by applying a suitable unit of the variable or by summing of the proper period. So, the daily AC electrical energy ($E_{AC,d}$) and the monthly AC electrical energy ($E_{AC,m}$) can be used in Eq. 1 to determine daily and monthly final field (h/day and h/month). In Eq. 4, if the solar irradiance on the plane of the array is related to daily ($H_{POA,d}$) or monthly values ($H_{POA,m}$), then the reference yield will be in *h/day* or *h/month.*

3.2.2. Life-cycle assessment (LCA)

LCA is a decision support tool capable of providing the decision maker with an evaluation of the environmental performance of a product, system and/or service. Internationally LCA is being used to assess the environmental impacts of solar PV systems e.g. to aid a decision on choosing between several solar cell technologies for technology selection in solar PV plants as well as to understand which type of power plant is better in terms of environmental impacts. This desertation employs LCA as per the *Figure 3.2*, a rigorous and standardized methodology (ISO 14040 series), to evaluate the environmental impacts associated solar power plant installations in India.

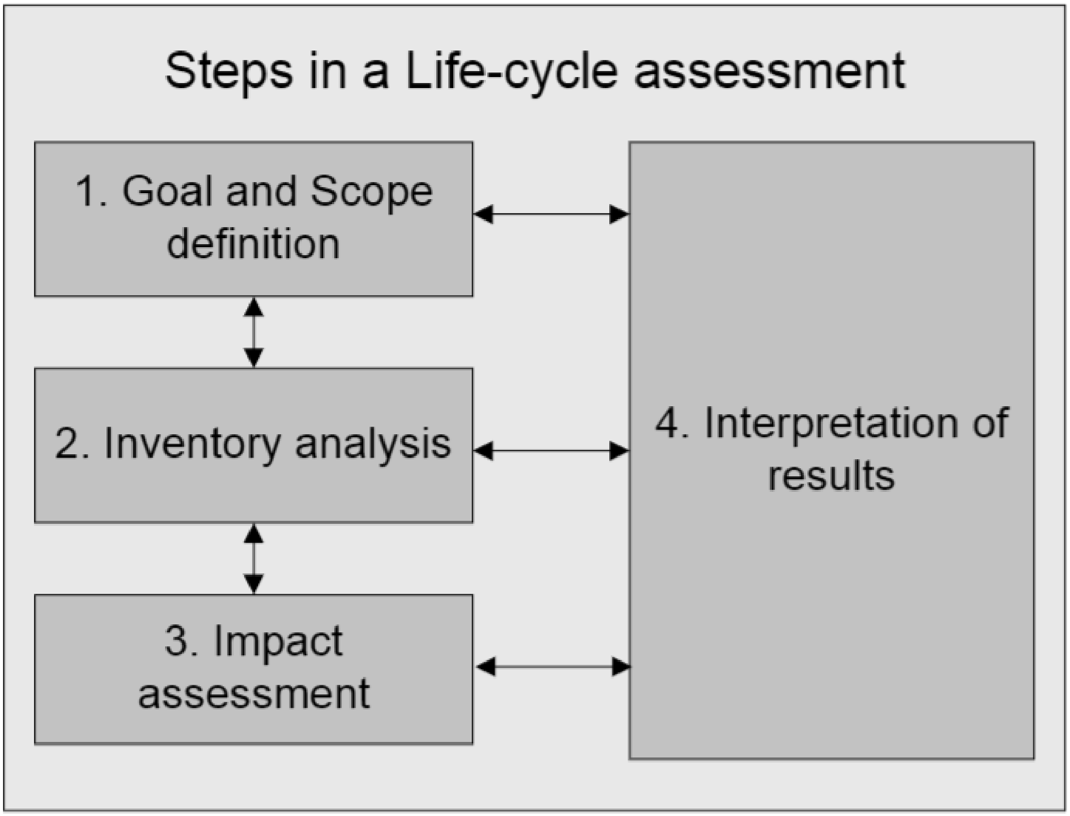


Figure 3.2. *Steps in Life-cycle assessment (modified according to ISO, 2006).*

By encompassing all stages from system component manufacturing to operation and potential end-of-life, the LCA framework provides a holistic understanding of the environmental burdens of solar power plant installations. The findings will contribute to a more comprehensive understanding of the environmental trade-offs.

3.2.3. Techno-economic Assessment (TEA)

TEA based on an equivalent uniform annual cash flow (EUAC) is more advisable. This is because the goal is to estimate the service cost, and EUAC is a method of calculating the total cost of a project over its lifetime, considering both initial and ongoing costs.

The lifecycle costing approach will involve the following steps:

- Identify all the costs associated with solar power plant systems
- Calculate the present value of all the costs. This can be done by discounting the future costs to their present value, using a discount rate that reflects the time value of money.
- Calculate the EUAC by dividing the present value of the costs by the number of years over which the costs will be incurred.
- The results of the life cycle costing analysis will provide information on the cost-effectiveness of solar PV systems. This information can be used to make decisions about whether to implement the system, and about the best way to implement it.

Eq. (3.6) represents the generic model for life cycle costing.

$$Life\ Cycle\ Costing\ = Capital\ Cost + Recurring\ Costs - Residual\ Value \quad (3.6)$$

From Eq. (3.6), the recurring costs are the operations and maintenance costs associated with the solar PV plant and in some cases disposal costs to be estimated especially to know the cost benefits of end-of-life solar PV plant assets (that could be due to any reasons); considering this cost, the recurring cost can be estimated as shown in Eq. (3.7).

$$Recurring\ Costs = Lifetime\ Operations\ Cost + Lifetime\ Maintenance\ Costs + Disposal\ Costs \quad (3.7)$$

Up on substituting Eq. (3.7) in Eq. (3.6), and by taking the principles of economics on present value, the overall life cycle costing can be represented as Eq. (3.8)

$$Life\ Cycle\ Costing = Capital\ Cost + Present\ Value\ of\ Lifetime\ Operations\ Cost + Present\ Value\ of\ Lifetime\ Maintenance\ Costs + Present\ Value\ of\ Disposal\ Costs - Present\ Value\ of\ Residual\ Value \quad (3.8)$$

The LCC calculation involves the following steps:

- Determination of costs and cash flows over the system life or considered time frame.
- Determination of an appropriate real interest or discount rate(s).
- Calculate a discounting factor for each year over the system life; the discount factor is given in Eq. (3.9):

  $$DF_t = \left\{\frac{1}{(1+i)^n}\right\} \quad (3.9)$$

  where i is the discount rate, and n is the number of years.

- For each year's cash flows, sum all incomes and expenses to determine the net cash flow for that year in nominal terms.
- Multiply each year's net cash flow by the appropriate discount factor.
- Sum the discounted net cash flows to derive the net present value.
- Estimate the life cycle cost.

The LCC analysis allows us to evaluate between investments by summing the present value of all future incomes and expenses, but that does not give us an insight into the expected cash flows that will occur. A common engineering cost approach for this evaluation is the equivalent uniform annual cash flow (EUAC) approach. The EUAC thus provides consistency in the cost analysis, see Eq. (3.10).

$$EUAC = LCC \times \frac{i(1+i)^n}{(1+i)^{n-1}} \tag{3.10}$$

The LCC method described above is leveraged to solar PV system installation variants that are discussed earlier; see Eq. (3.11).

$$LCC = CapEx_C + \left\{\frac{i\times(i+1)^n}{(i+1)^n-1} \times OpEx_C\right\} - \left\{\frac{i}{(i+1)^n-1} \times RV_C\right\} \tag{3.11}$$

where $CapEx_C$ is the sum of the capital cost of the infrastructure in a region c; $OpEx_C$ is the operational and maintenance costs in a region c; and RV_C is the residual value in a region c.

Based on system descriptions provided earlier, the data required for the LCC model as per the model described above were collected. We built the LCC model in excel based on the modelling Eqs. (3.6) to (3.11) for understanding the economic feasibility.

The individual cost components we considered for the LCC approach are as follows.

- Capital Cost: It is either the purchase price of an item or the initial cost of the set-up in the case of a project. In most cases, it also includes the cost of installation.
- Recurring Cost: It represents all those costs after the purchase which primarily include operating and maintenance expenses.
- Operations Cost: These costs are associated with the usage of the assets, for example, energy, chemicals, membrane and other related consumables.
- Maintenance Cost: These costs are associated with repair and replacement expenses.
- Disposal Cost: These costs are incurred at the time of asset disposal, for example, landfilling.
- Residual Costs: These represent the asset's value at the end of its useful life.

3.4. Framework for creating photovoltaic based sustainable communities

The visual shown in *Figure 3.3* captures the framework I developed for creating PV-based sustainable communities, showcasing the interconnected components and their logical flow. The diagram provides a structured breakdown of the fundamental questions and principles that guided the framework's creation, emphasizing the integration of solar energy into sustainable community design.

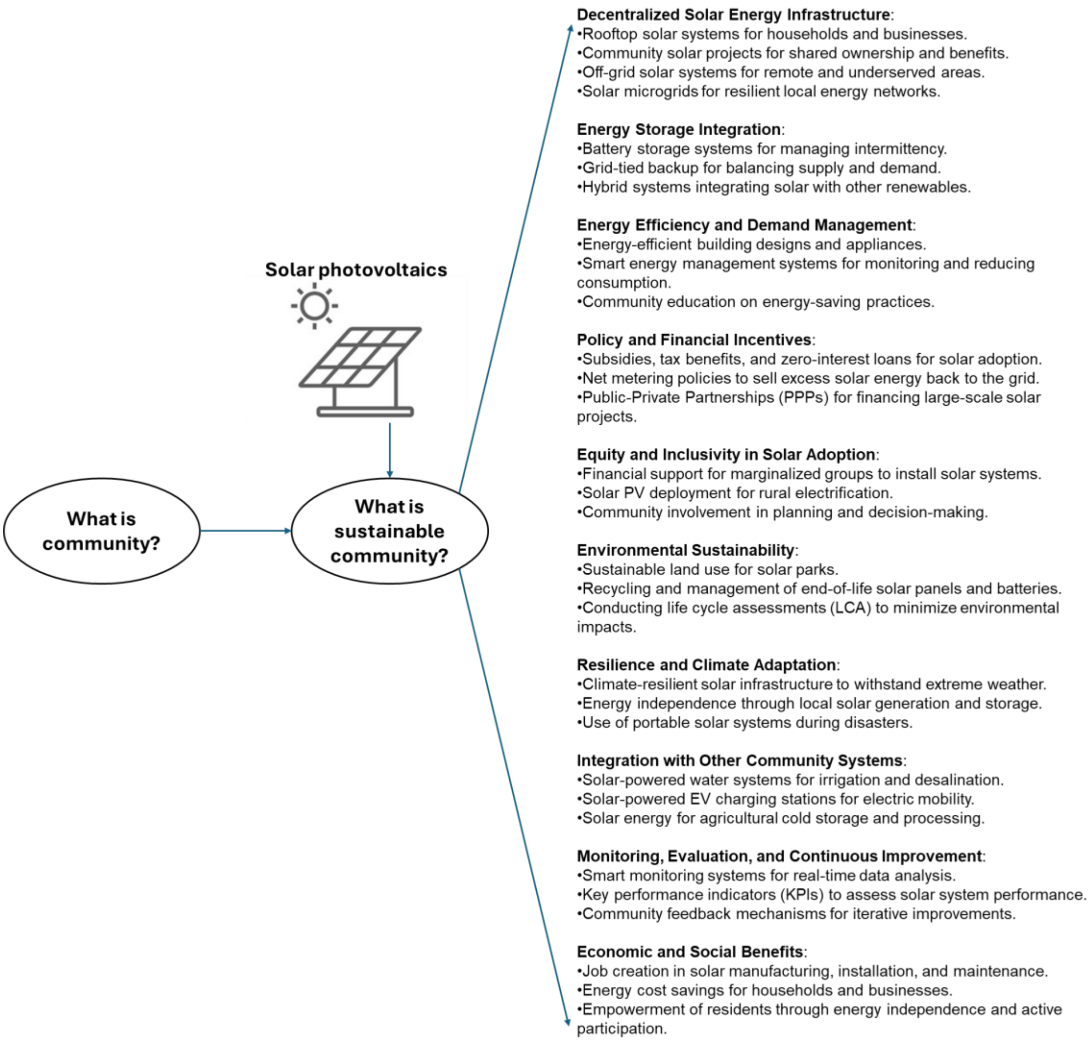


Figure 3.3. *Framework showing the core principles and logical steps to be considered while developing the photovoltic based sustainbale communities (Source: Own Illustration).*

Based on the developed framework, a questionarie was prepared and using this a survey was conducted to do the qualitative assessment on the role of photovoltaic installations variants in creating sustinable communties in India. To provide a structured and comprehensive approach to analyzing the complexities, I later introduced the well established TESEI analytical framework available in the literature.

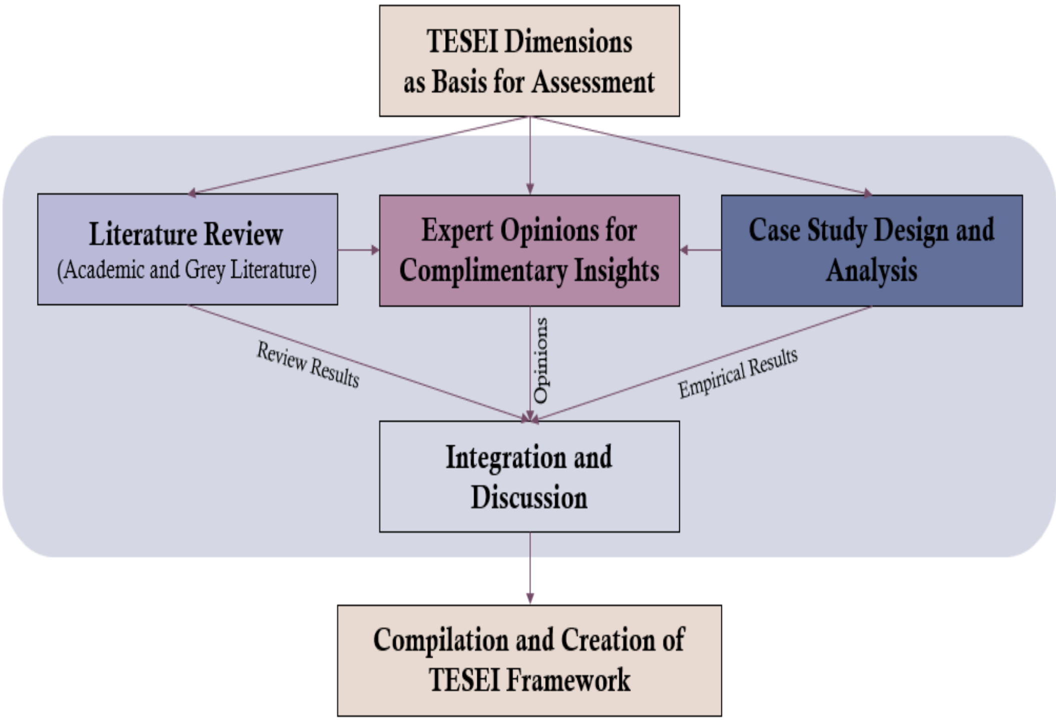


Figure 3.4. *Applying TESEI Analytical Framework (Source: Dheeraj, 2025)*

This framework, encompassing five key dimensions – Technological, Economic, Social, Environmental, and Institutional – and their associated sub-factors, offers a holistic lens through which to examine the role of PV in sustainable communties. The dimensions and factors incorporated within TESEI were carefully selected based on an extensive review of existing literature, the identified research gaps, preliminary insights gleaned from the designed case study, and opinions from experts in the field. As shown in *Figure 3.3*, by integrating these diverse perspectives, the

TESEI framework aims to facilitate a nuanced understanding of the multifaceted issues at play and inform the development of effective and sustainable solutions. The process begins with “TESEI Dimensions as Basis for Assessment”, which informs three parallel research streams: a “Literature Review” encompassing academic and grey literature as a data, gathering “Expert Opinions for Complimentary Insights”, and “Case Study Design and Analysis”. The literature review yields “Review Results”, expert consultations provide “Opinions”, and the case study generates “Empirical Results”. These three streams converge in an “Integration and Discussion” phase, where the findings are synthesized. Finally, this integrated understanding leads to the “Compilation and Creation of TESEI Framework”, representing the culmination of the research effort.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results along with a discussion focusing on how photovoltaic installations variants can promote the sustainable communtieis concept in India.

4.1. Energy performance of solar photovoltaic plants in India

The results presented in Table 4.1. summarize key performance parameters and environmental conditions critical for the design and optimization of photovoltaic (PV) systems. These parameters outline the operational performance range of PV systems under varying climatic and geographical conditions, providing a reference for assessing site-specific energy outputs and efficiency.

The specific photovoltaic power output (PVOUT), a measure of energy output per unit of installed PV capacity, ranges between 3.39 and 5.24 kWh/kWp. This variation reflects differences in solar energy availability, system design, and local environmental conditions. Solar irradiation metrics are crucial for PV system performance, with Direct Normal Irradiation (DNI), Global Horizontal Irradiation (GHI), Diffuse Horizontal Irradiation (DIF), and Global Tilted Irradiation (GTI) values ranging from 2.51 to 6.26 kWh/m^2. These metrics capture both direct and diffuse solar energy under horizontal and tilted orientations, which are essential for determining energy generation potential and the optimal orientation of PV modules.

The optimum tilt angle (OPTA) of PV modules is observed to lie between 10° and 35°, ensuring maximum solar energy capture based on location-specific solar geometry. Environmental factors such as air temperature (TEMP), ranging from -14.3°C to 29.1°C, and terrain elevation (ELE), spanning from -2 m to 8,586 m, further influence the performance of PV systems by impacting module efficiency and energy conversion rates.

Table 4.1. Solar photovoltaic power plant operating performance indicators for India

Parameter	**Minimum Value**	**Maximum Value**	**Unit**
Specific Photovoltaic Power Output	3.39	5.24	kWh/kWp
Direct Normal Irradiation	2.51	5.81	kWh/m²
Global Horizontal Irradiation	3.77	5.64	kWh/m²
Diffuse Horizontal Irradiation	1.52	2.65	kWh/m²
Global Tilted Irradiation	4.13	6.26	kWh/m²
Optimum Tilt of PV Modules	10	35	°
Air Temperature	-14.3	29.1	°C
Terrain Elevation	-2	8586	m

The results in Figure 4.1. illustrate the distribution of photovoltaic (PV) power output and its monthly variation, providing insights into the spatial and temporal performance of PV systems. These visualizations highlight the practical potential of PV systems across evaluated regions and their output variation over the year.

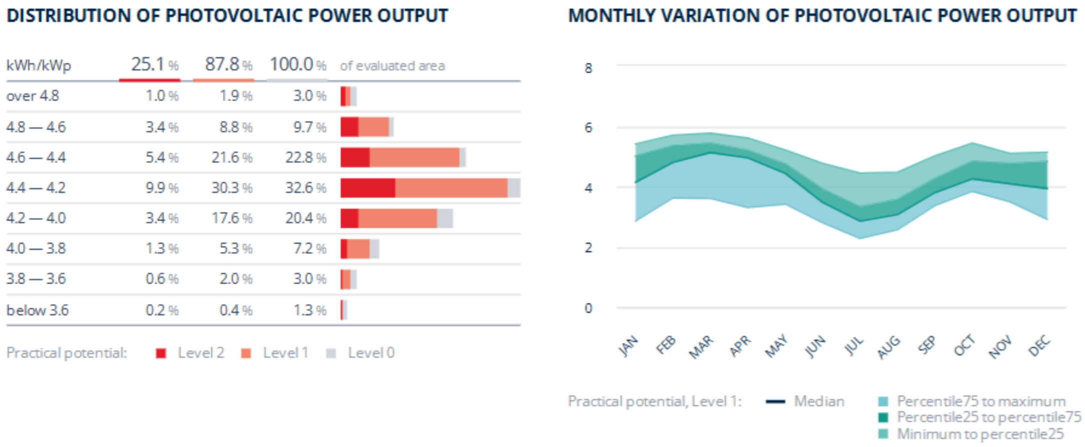


Figure 4.1. Distribution of photovoltiac power output along with monthly variation for India (Source: Modelled Results from SolarGIS tool)

The distribution data (left panel) categorizes specific photovoltaic power outputs (in kWh/kWp) into performance ranges, with corresponding percentages of the evaluated area falling into each range. Approximately 25.1% of the evaluated area achieves a practical potential of 4.4–4.6 kWh/kWp, making it the most common output range. Outputs between 4.2–4.4 kWh/kWp and 4.6–4.8 kWh/kWp cover 17.6% and 21.6% of the area, respectively, further contributing to the majority of regions with moderate to high performance. Only 1.0% of the area achieves outputs over 4.8 kWh/kWp, indicating limited high-performance zones, while a small fraction (0.2%) falls below 3.6 kWh/kWp, representing the least productive areas. The practical potential is categorized into Level 0 (low), Level 1 (moderate), and Level 2 (high performance), with 87.8% of the evaluated area achieving at least moderate potential (Level 1 or higher). This distribution highlights the geographical variability in PV power output, influenced by factors such as solar irradiance, climatic conditions, and regional characteristics. Regions with higher performance potential are likely to be characterized by higher direct normal irradiation (DNI) and favorable environmental conditions.

The monthly variation of PV power output (right panel) is depicted as a range of values, including the median, interquartile range (percentile 25 to percentile 75), and overall variability from minimum to maximum. The median PV power output follows a seasonal trend, peaking during April to June at approximately 5–6 kWh/kWp and dipping during the monsoon months of July to September, where values drop to 3–4 kWh/kWp. This seasonal trend corresponds to variations in solar irradiance, cloud cover, and weather patterns. The interquartile range indicates moderate variability across regions during most months, with wider variability during the monsoon period due to differing climatic impacts across evaluated areas. This demonstrates the influence of seasonality on PV system performance, emphasizing the need for energy storage systems or supplementary energy sources during low-output months.

The distribution and monthly variation of PV power output are significant for India, where PV systems must be tailored to address both geographical and seasonal variations. High-output regions, such as Rajasthan and Gujarat, fall within the higher performance ranges, while areas with lower DNI, such as parts of Northeastern India, may fall into the lower output ranges. The seasonal dip during monsoon months further underscores the importance of integrating energy storage or hybrid systems to ensure reliable energy supply throughout the year.

The results presented in Figure 4.2. illustrate key performance indicators for photovoltaic (PV) systems, specifically the average theoretical potential based on

Global Horizontal Irradiation (GHI) and the seasonality index. These metrics provide valuable insights into the overall energy generation potential and the seasonal variability of PV systems across different regions.

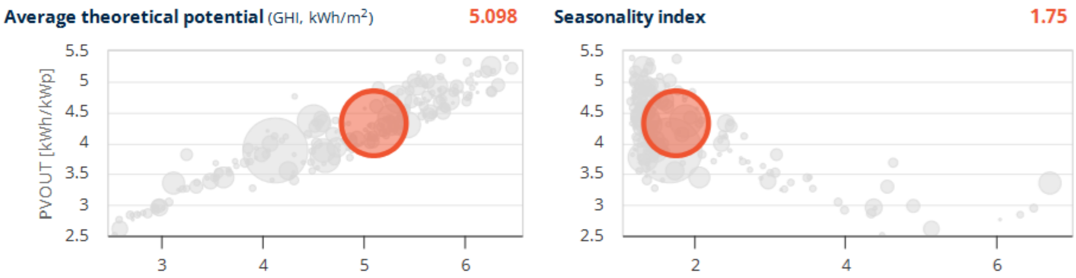


Figure 4.2. Average theortical power performance of photovoltiac power plant with seasonloty index showing the variaiton range for India (Source: Modelled Results from SolarGIS tool)

The left panel of the figure represents the relationship between the average theoretical potential (calculated from GHI in kWh/m²) and the specific photovoltaic power output (PVOUT) in kWh/kWp. The average theoretical potential is observed to be 5.098 kWh/m², with PVOUT values ranging from approximately 2.5 to 5.5 kWh/kWp. A strong positive correlation is evident between GHI and PVOUT, as regions with higher GHI values yield higher PV power outputs. The red-highlighted cluster in the graph represents regions with the most significant contribution to the theoretical potential, indicating a concentration of areas with both high GHI and PVOUT values. These regions are ideal for harnessing solar energy, offering optimized energy generation potential. This relationship underscores the importance of selecting locations with high GHI levels when designing PV systems to maximize efficiency and energy yield.

The right panel of the figure illustrates the seasonality index, which measures the variability in PV power output throughout the year. The seasonality index for the evaluated regions is 1.75, indicating moderate seasonal variation in solar energy availability. The PVOUT values range from 2.5 to 5.5 kWh/kWp, with the red-highlighted cluster again representing regions with stable performance despite seasonal changes. A lower seasonality index reflects regions with relatively consistent solar energy availability, while higher values indicate more pronounced seasonal fluctuations. The data suggest that areas with a seasonality index close to the overall average are better suited for reliable energy generation year-round. Regions with higher seasonality may require supplementary energy storage systems or hybrid solutions to ensure consistent power supply during low-output months.

For India, the average theoretical potential of 5.098 kWh/m^2 and a seasonality index of 1.75 broadly align with the country's solar energy characteristics. Regions with high GHI values, such as Rajasthan, Gujarat, and parts of Maharashtra, are likely to fall within the high-performance clusters observed in the graphs. Conversely, regions with higher seasonal variability, such as the Northeastern states or areas with prolonged monsoon seasons, may exhibit a higher seasonality index.

For India, PV systems installed across various states will broadly operate within these performance ranges. However, given the country's diverse climatic zones and geographical variations, significant state-wise differences in solar energy availability and environmental conditions are expected. For instance, regions with higher direct irradiance, such as Rajasthan and Gujarat, are likely to achieve greater energy outputs compared to regions with higher diffuse irradiance or lower DNI values, such as

Northeastern states. Similarly, variations in optimum tilt angles and air temperature will influence the energy capture and efficiency of PV systems across different locations.

Table 4.2. Specific photovoltaic power output distribution of solar power plants installed in various states and union territories of India (Source: Modelled Results from SolarGIS tool).

State/UTs	Energy Performance (kWh/kWp)	
Andaman and Nicobar	more than 4.20	1.5 %
	4.20 – 4.00	66.8 %
	4.00 – 3.80	25.4 %
	less than 3.80	6.3 %
		100.0 %
Andhra Pradesh	more than 4.40	11.6 %
	4.40 – 4.20	45.7 %
	less than 4.20	42.7 %
		100.0 %
Arunachal Pradesh	more than 4.00	1.1 %
	4.00 – 3.80	1.1 %
	3.80 – 3.60	3.2 %
	3.60 – 3.40	17.6 %
	3.40 – 3.20	24.0 %
	3.20 – 3.00	23.2 %
	3.00 – 2.80	16.3 %
	2.80 – 2.60	9.2 %
	2.60 – 2.40	3.4 %
	less than 2.40	0.9 %
		100.0 %
Assam	more than 4.00	2.5 %
	4.00 – 3.80	34.4 %
	3.80 – 3.60	52.5 %
	less than 3.60	10.6 %
		100.0 %

Bihar	more than 4.20	2.5 %
	4.20 – 4.00	33.0 %
	4.00 – 3.80	55.4 %
	less than 3.80	9.1 %
		100.0 %
Chandigarh	more than 4.00	100.0 %
		100.0 %
Chhattisgarh	more than 4.40	21.6 %
	less than 4.40	78.4 %
		100.0 %
Dadra and Nagar Haveli	more than 4.40	6.5 %
	less than 4.40	93.5 %
		100.0 %
Daman and Diu	more than 4.60	30.7 %
	less than 4.60	69.3 %
		100.0 %
Goa	more than 4.40	7.5 %
	4.40 – 4.20	60.3 %
	less than 4.20	32.2 %
		100.0 %
Gujarat	more than 4.80	1.9 %
	4.80 – 4.60	70.8 %
	4.60 – 4.40	25.2 %
	less than 4.40	2.1 %
		100.0 %
Haryna	more than 4.20	23.3 %
	less than 4.20	76.7 %
		100.0 %
Himachal Pradesh	more than 5.00	8.4 %
	5.00 – 4.80	5.9 %
	4.80 – 4.60	8.3 %
	4.60 – 4.40	12.9 %
	4.40 – 4.20	22.1 %
	4.20 – 4.00	26.2 %
	4.00 – 3.80	6.7 %
	3.80 – 3.60	3.5 %
	less than 3.60	6.0 %
		100.0 %

Jammu and Kashmir	more than 5.40	7.9 %
	5.40 – 5.20	7.5 %
	5.20 – 5.00	7.3 %
	5.00 – 4.80	8.1 %
	4.80 – 4.60	8.5 %
	4.60 – 4.40	12.5 %
	4.40 – 4.20	15.6 %
	4.20 – 4.00	18.7 %
	4.00 – 3.80	7.7 %
	less than 3.80	6.2 %
		100.0 %
Jharkhand	more than 4.40	6.3 %
	4.40 – 4.20	62.8 %
	4.20 – 4.00	24.3 %
	less than 4.00	6.6 %
		100.0 %
Karnataka	more than 4.40	47.1 %
	4.40 – 4.20	45.9 %
	less than 4.20	7.0 %
		100.0 %
Kerala	more than 4.20	21.1 %
	4.20 – 4.00	49.2 %
	4.00 – 3.80	23.8 %
	less than 3.80	5.9 %
		100.0 %
Lakshadweep	more than 4.40	39.5 %
	less than 4.40	60.5 %
		100.0 %
Madhya Pradesh	more than 4.60	1.5 %
	4.60 – 4.40	71.3 %
	4.40 – 4.20	25.9 %
	less than 4.20	1.3 %
		100.0 %
Maharashtra	more than 4.40	36.4 %
	4.40 – 4.20	61.2 %
	less than 4.20	2.4 %
		100.0 %

Manipur	more than 4.20	1.3 %
	4.20 – 4.00	39.4 %
	4.00 – 3.80	42.8 %
	3.80 – 3.60	13.9 %
	less than 3.60	2.6 %
		100.0 %
Meghalaya	more than 4.00	1.4 %
	4.00 – 3.80	57.6 %
	3.80 – 3.60	38.0 %
	less than 3.60	3.0 %
		100.0 %
Mizoram	more than 4.20	12.5 %
	4.20 – 4.00	65.1 %
	less than 4.00	22.4 %
		100.0 %
NCT of Delhi	more than 4.00	82.5 %
	less than 4.00	17.5 %
		100.0 %
Nagaland	more than 4.00	3.3 %
	4.00 – 3.80	37.9 %
	3.80 – 3.60	42.6 %
	3.60 – 3.40	13.8 %
	less than 3.40	2.4 %
		100.0 %
Odisha	more than 4.40	1.1 %
	4.40 – 4.20	56.0 %
	less than 4.20	42.9 %
		100.0 %
Puducherry	more than 4.40	1.4 %
	4.40 – 4.20	87.3 %
	less than 4.20	11.3 %
		100.0 %
Punjab	more than 4.20	12.8 %
	less than 4.20	87.2 %
		100.0 %

Rajasthan	more than 4.80	**14.7** %
	4.80 – 4.60	**43.5** %
	4.60 – 4.40	**28.5** %
	less than 4.40	**13.3** %
		100.0 %
Sikkim	more than 4.60	**7.4** %
	4.60 – 4.40	**4.8** %
	4.40 – 4.20	**4.3** %
	4.20 – 4.00	**4.5** %
	4.00 – 3.80	**5.8** %
	3.80 – 3.60	**11.6** %
	3.60 – 3.40	**17.9** %
	3.40 – 3.20	**17.5** %
	3.20 – 3.00	**12.5** %
	less than 3.00	**13.7** %
		100.0 %
Tamil Nadu	more than 4.40	**7.3** %
	4.40 – 4.20	**75.1** %
	4.20 – 4.00	**14.3** %
	less than 4.00	**3.3** %
		100.0 %
Telangana	more than 4.40	**29.9** %
	4.40 – 4.20	**67.7** %
	less than 4.20	**2.4** %
		100.0 %
Tripura	more than 4.00	**4.6** %
	less than 4.00	**95.4** %
		100.0 %
Uttar Pradesh	more than 4.40	**2.3** %
	4.40 – 4.20	**10.6** %
	4.20 – 4.00	**76.8** %
	less than 4.00	**10.3** %
		100.0 %

Uttarakhand	more than 5.20	1.3 %
	5.20 – 5.00	1.5 %
	5.00 – 4.80	2.8 %
	4.80 – 4.60	10.5 %
	4.60 – 4.40	21.4 %
	4.40 – 4.20	25.5 %
	4.20 – 4.00	27.0 %
	4.00 – 3.80	5.4 %
	3.80 – 3.60	2.6 %
	less than 3.60	2.0 %
		100.0 %
West Bengal	more than 4.20	3.5 %
	4.20 – 4.00	36.3 %
	4.00 – 3.80	42.3 %
	3.80 – 3.60	13.4 %
	3.60 – 3.40	2.5 %
	less than 3.40	2.0 %
		100.0 %

Table 4.3. Capacity Utilization Factor (CUF) for solar power plants for various solar power plants in different states and union teritories of India (Source: Modelled Results from SolarGIS tool)

State	Ground Mounted Capacity (MW)	Rooftop Capacity (MW)	Off-Grid Capacity (MW)	Total Capacity (MW)	Generation (MU)	CUF (%)
Chhattisgarh	998.91	146.2	390.73	1535.84	534.3	11.88
Ladakh	6	5	0	11	0	0
Madhya Pradesh	4865.23	627.7	102.04	5594.97	2426.65	14.81
Himachal Pradesh	203	62.9	34.58	300.48	68.6	7.8
Manipur	0.6	10.2	6.08	16.88	2.17	4.39
Chandigarh	6.34	71.7	0.81	78.85	1.72	0.74
Jammu and Kashmir	2.49	42.2	29.8	74.49	0	0
Nagaland	0	1	2.17	3.17	0	0
Sikkim	0.52	5.12	1.92	7.56	0	0
Delhi	9.84	341.3	1.46	352.6	51.63	5
Bihar	196.06	193.8	21.28	411.14	113.01	9.39
Dadra and Nagar Haveli and Daman and Diu	14.3	105.6	0	119.9	4.96	1.41
Gujarat	15896.24	5835.3	173.01	21904.55	7946.78	12.39
Jharkhand	21	93.04	86.32	200.36	4.41	0.75

Puducherry	1.03	67.8	0.18	69.01	5.94	2.94
Tripura	5.57	12.2	11.34	29.11	4.36	5.11
Uttarakhand	541.05	273.71	20.96	835.72	98.8	4.04
Rajasthan	29801.74	1710	805.45	32317.19	20529.89	21.7
Goa	1.95	57.7	1.49	61.14	14.28	7.98
West Bengal	240.35	67.13	13.14	320.62	116.05	12.36
Lakshadweep	2.45	1.6	2.52	6.57	0.02	0.12
Odisha	574.5	106.8	42.34	723.64	269.31	12.71
Maharashtra	7982.71	3745.4	1608.71	13336.82	2796.85	7.16
Arunachal Pradesh	1.27	6.68	6.9	14.85	1.32	3.04
Andaman and Nicobar Islands	25.05	5.6	0.27	30.92	3.86	4.26
Haryana	267.76	889.6	1019.65	2177.01	385.78	6.05
Kerala	323.21	1444.2	24.93	1792.34	579.99	11.05
Andhra Pradesh	5006.34	428.6	88.34	5523.28	2759.8	17.07
Uttar Pradesh	2776.34	382.5	324.72	3483.56	1868.85	18.32
Others	0	0	45.01	45.01	0	0
Telangana	4360.49	633.5	8.71	5002.7	2277.14	15.55
Karnataka	9266.28	755.4	39.16	10060.84	5248.65	17.82
Assam	126	107.9	9.44	243.34	95.48	13.4
Punjab	886.27	503.4	81.76	1471.43	527.02	12.23
Meghalaya	0	0.21	4.07	4.28	0	0
Tamil Nadu	9621.08	1132.5	70.4	10823.98	6003.19	18.94
Mizoram	22	3	6.39	31.39	10.51	11.43

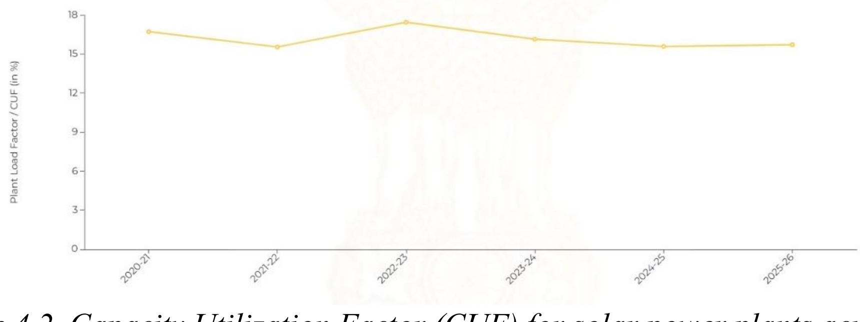
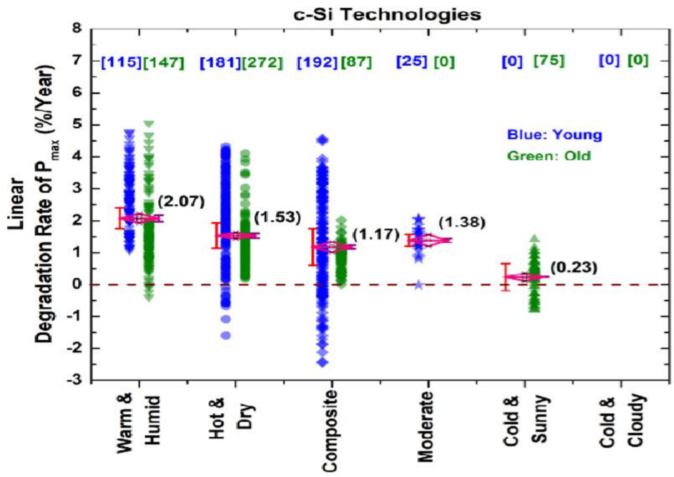


Figure 4.2. Capacity Utilization Factor (CUF) for solar power plants across six years, from 2020–21 to 2025–26 in India. (Source: NITI Aayog, MNRE, CEA)

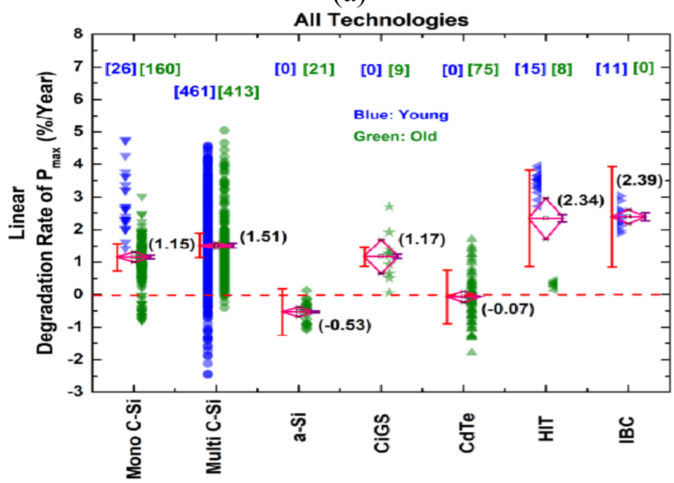
Based on the observations from the data shown in *Table 4.3.,* CUF of various solar photovoltiac plants and their installation variants can be understood. The line chart in *Figure 4.2.* depicts the trend of the Plant Load Factor (PLF) or Capacity Utilization Factor (CUF) for solar power plants across six years, from 2020–21 to 2025–26. CUF represents the efficiency of a solar power plant in generating electricity as a percentage of its maximum potential output under ideal conditions. This performance metric is crucial for understanding the operational effectiveness and reliability of solar energy systems over time. The CUF for solar power plants displays a fluctuating trend over the analyzed years, with values ranging from approximately 15% to 18%: In 2020–21, the CUF reached its highest value at approximately 18%, indicating optimal performance during this year. The CUF experienced a decline in 2021–22, dropping to around 15%, potentially due to factors such as reduced solar irradiance, operational inefficiencies, or maintenance issues. A slight recovery was observed in 2022–23, with the CUF increasing to around 16%, reflecting improved operational conditions. From 2023–24 onwards, the CUF stabilized at approximately 15%, maintaining steady performance but failing to recover to the peak levels of 2020–21.

The observed fluctuations in the CUF can be attributed to several factors, including variability in solar irradiation, seasonal effects, degradation of solar modules, and operational challenges such as grid constraints or plant maintenance. The overall downward trend from the highest CUF value in 2020–21 suggests a need for interventions to improve operational efficiencies and reduce performance losses. The CUF values in the range of 15–18% are consistent with the typical performance range for solar power plants in India, where ground-mounted PV systems usually exhibit CUFs in this range due to climatic and technological factors. The stable CUF from 2023–24 to 2025–26 indicates that solar plants are operating reliably but may not be reaching their full potential. To enhance CUF, measures such as adopting advanced technologies (e.g., bifacial modules and tracking systems), ensuring regular maintenance, and minimizing grid curtailments can be implemented.

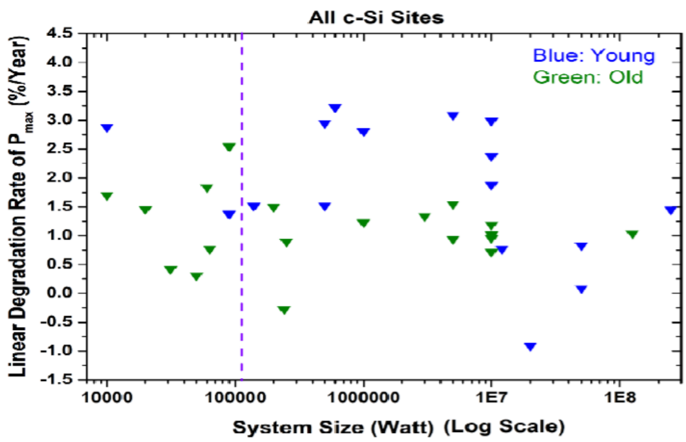
The results presented in Figures 4.3 (a), (b), and (c) provide a comprehensive analysis of the linear degradation rates of photovoltaic (PV) modules, expressed as a percentage of the maximum power output lost per year (%/year). The analysis considers various factors, including climatic conditions, PV technologies, and system sizes, to understand the performance and reliability of PV systems over time. Figure 4.3(a) represents degradation rates across climatic conditions for c-si technologies. This figure focuses on crystalline silicon (c-Si) technologies under different climatic conditions, with degradation rates compared between young (blue) and old (green) PV systems. The highest degradation rate is observed in warm and humid climates, with an average rate of 2.07% per year, indicating significant module performance losses in such regions. Hot and dry climates exhibit a lower degradation rate of 1.53% per year, reflecting less stress from moisture but potential impact from high temperatures. Composite (1.17%) and moderate (1.38%) climates show relatively stable PV performance. The lowest degradation rate is observed in cold and sunny climates (0.23%), indicating favorable conditions for long-term PV performance. Young PV systems tend to exhibit slightly better performance compared to older systems across all climatic conditions, as shown by the clustering of blue markers below the green markers. This highlights the impact of aging on module degradation. Figure 4.3(b) represents degradation rates across pv technologies. This figure compares degradation rates across different PV technologies, including Mono c-Si, Multi c-Si, a-Si, CIGS, CdTe, HIT, and IBC. Mono c-Si and Multi c-Si technologies exhibit average degradation rates of 1.15% and 1.51% per year, respectively, making them the most common and reliable technologies. Thin-film technologies such as a-Si (-0.53%) and CdTe (-0.07%) show negligible or even negative degradation rates in some cases, suggesting improved stability under specific conditions. Advanced technologies like HIT (2.34%) and IBC (2.39%) show relatively higher degradation rates, possibly due to the complexity of their structure or susceptibility to specific stress factors. Similar to climatic conditions, younger systems consistently outperform older systems, as evident from the lower degradation rates for blue markers compared to green markers. Figure 4.3(c) represents degradation rates based on system size. This figure evaluates degradation rates for c-Si technologies as a function of system size, measured in watts (log scale), with differentiation between young (blue) and old (green) systems. Degradation rates are generally lower for larger systems, particularly for installations exceeding 100,000 W (100 kW). This trend may be attributed to better operation and maintenance (O&M) practices adopted for utility-scale projects compared to smaller systems. Smaller systems (<100 kW) exhibit more scattered degradation rates, reflecting diverse performance outcomes due to varying design, installation quality, and environmental factors. Young systems show slightly lower degradation rates across all system sizes, reinforcing the notion that newer modules perform better and degrade more slowly than older ones.



(a)



(b)



(c)

Figure 4.3. illustrates the linear degradation rate of maximum power output (Pmax) for PV modules based on (a). Climatic zones,(b). PV technologies, (c). System size.

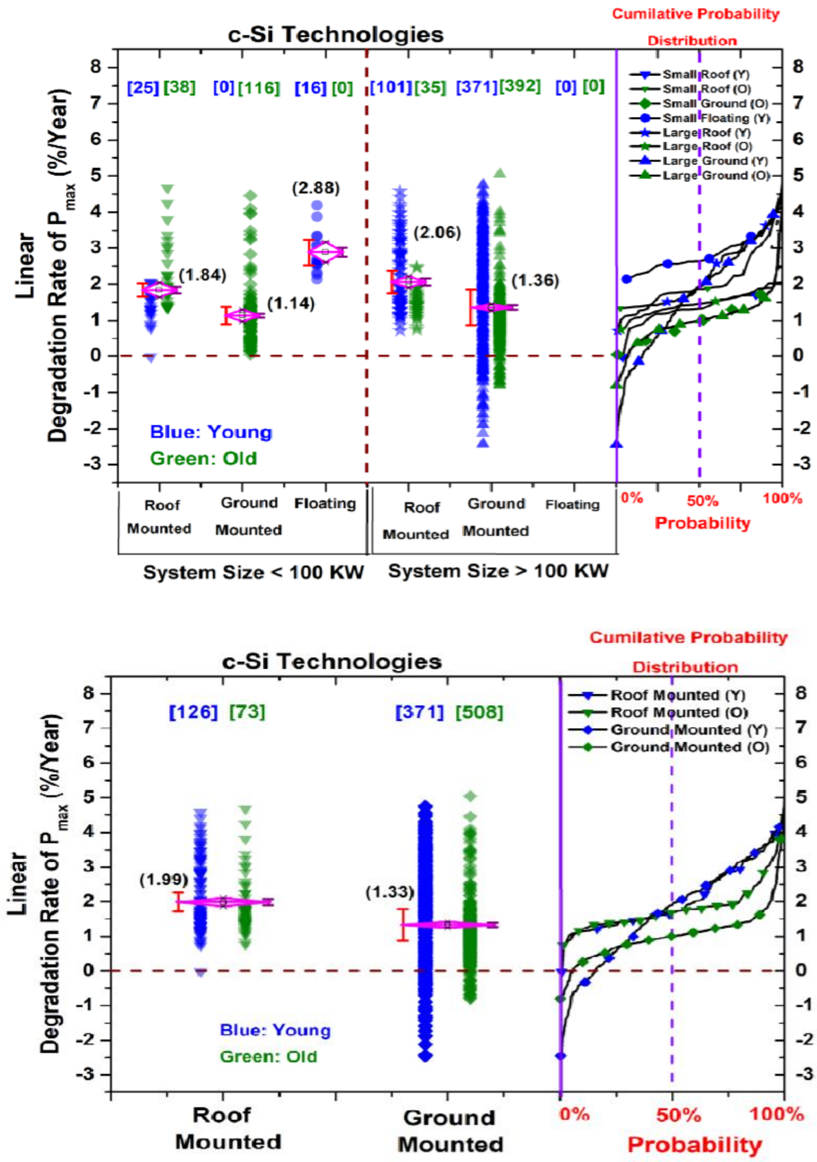


Figure 4.4. Linear Degradation Rate of Pmax for Different Types of Installations and System Size; Linear Degradation Rate of Pmax for Roof Rack and Ground Rack mounted c-Si PV modules. (Source: Results from All India Degradation Reports, 2022).

Figure 4.4 analyzes the linear degradation rates of Pmax (%/year) for crystalline silicon (c-Si) PV modules based on system size, mounting type, and cumulative probability distribution. Roof-mounted systems exhibit higher degradation rates (1.84%/year) compared to ground-mounted systems (1.14%/year). Floating systems show the highest degradation rate (2.88%/year), likely due to increased exposure to environmental stresses like humidity and temperature fluctuations. Ground-mounted systems perform better (1.36%/year) than roof-mounted systems (2.06%/year), reflecting better maintenance practices and stability in larger installations. Roof-mounted systems show a higher degradation rate (1.99%/year) compared to ground-mounted systems (1.33%/year), attributed to greater thermal stress and less effective ventilation in rooftop installations. The cumulative probability curves on the right highlight that the ground-mounted systems consistently achieve lower degradation rates across both young (blue) and old (green) systems, with steeper curves indicating more consistent performance. Roof-mounted systems exhibit wider variability, with a significant proportion of systems experiencing higher degradation rates.

4.2. Economic performance of solar photovoltaic plants in India

The *Figure 4.5*. compares the cost per kilowatt (kW) for rooftop and ground-mounted solar systems across various capacities (1 kW to 500 kW) based on the bill of materials data given in Appendix A. Rooftop systems start at a higher cost per kW (~₹40/kW for smaller systems) due to additional requirements like mounting structures and rooftop-specific design considerations. As system capacity increases, the cost gradually decreases, reaching approximately ₹35/kW for capacities of 500 kW. This decline reflects economies of scale, where the cost per unit reduces with larger installations. Ground-mounted systems maintain a relatively constant cost (~₹30/kW) across all capacities. This stability is due to simplified installation processes and the absence of structural reinforcements required for rooftop installations. Across all capacities, rooftop systems are consistently more expensive than ground-mounted systems, with a cost difference of about ₹5-10/kW. This premium is due to additional engineering, design, and safety measures needed for rooftop installations. The cost gap narrows slightly as capacity increases, but rooftop systems remain costlier for large-scale installations.

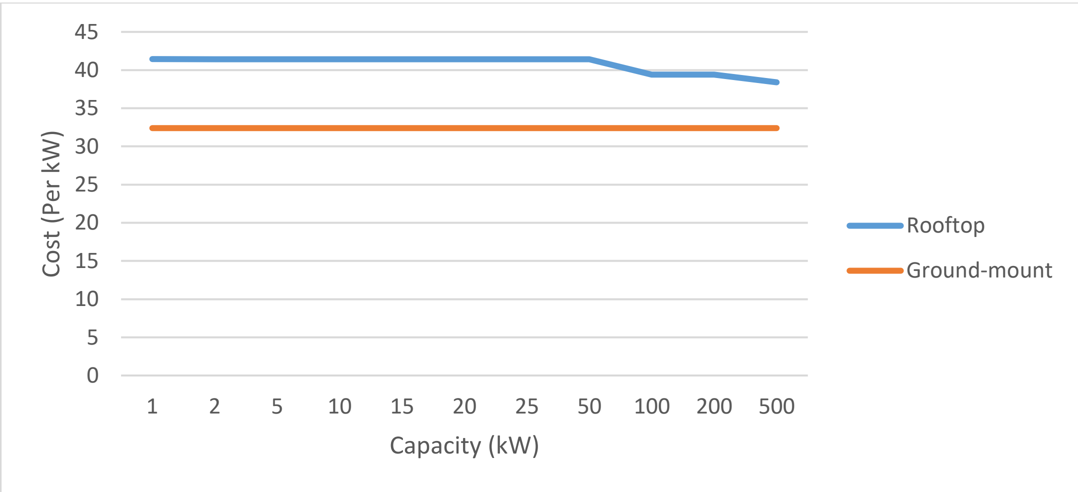
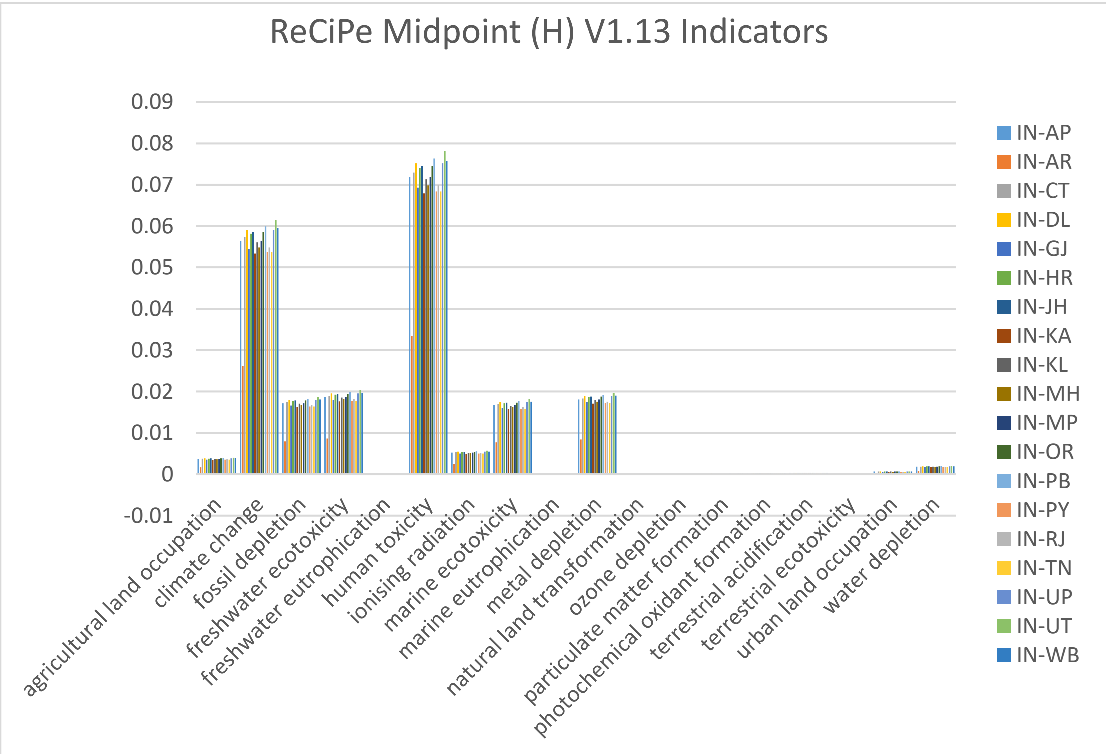


Figure 4.5. Cost comparsion of low kW to high kW scale solar power plant installations in India (Source: Modelled Results based on Data Collected from Sride Climate Investments)

4.3. Environmental performance of solar photovoltaic plants in India

The environmental impact assessment across 18 ReCiPe Midpoint (H) indicators highlights significant regional variations in resource use, emissions, and ecosystem impacts among Indian states and union territories (*see Figure 4.6.*). Urbanized and industrialized regions, such as Uttarakhand (IN-UT), Punjab (IN-PB), and Delhi (IN-

DL), consistently exhibit the highest impacts across key categories, including climate change (GWP100, 0.061395 kg CO_2-Eq in IN-UT), fossil depletion (FDP, 0.018683 kg oil-Eq in IN-UT), and water depletion (WDP, 0.002006 m^3 water in IN-UT). These areas also show elevated levels of human toxicity (HTPinf, 0.078145 kg 1,4-DC Eq) and marine eutrophication (MEP, 2.53E-05 kg N-Eq), indicating the influence of dense populations, industrial emissions, and agricultural runoff. In contrast, regions such as Arunachal Pradesh (IN-AR) and Andhra Pradesh (IN-AP) show significantly lower impacts, with climate change contributions as low as 0.026223 kg CO_2-Eq and fossil



depletion at 0.00798 kg oil-Eq, reflecting reduced industrial activity and resource use.

Figure 4.6. ReCiPe Midpoint (H) V1.13 Indicators for solar photovoltaic power plant installed in different states of India (Modelled Results Using SimaPro)

Notably, agricultural and urban land occupation (ALOP and ULOP) are highest in IN-UT (0.004017 m^2a and 0.000712 m^2a, respectively), driven by land use changes for infrastructure and development, while natural land transformation (NLTP) impacts are minimal across all states. Ozone depletion (ODPinf) and particulate matter formation (PMFP) remain relatively uniform, though higher in urbanized areas due to industrial and vehicular emissions. Interestingly, floating systems in IN-UT and IN-PB contribute disproportionately to freshwater ecotoxicity (FETPinf, 0.020305 kg 1,4-DC Eq) and marine ecotoxicity (METPinf, 0.01813 kg 1,4-DC Eq), likely due to chemical discharges and runoff.

4.4. Implication on building PV-based sustainaility in India

A PV-based sustainable community is built upon the integration of solar energy systems to meet energy demands in an environmentally sustainable, socially inclusive, and economically viable manner. The framework ensures that solar energy is not only adopted but optimized to create self-reliant, low-carbon, and equitable energy systems that foster the long-term well-being of the community. Below is a detailed stratgeis based on the framework disussed in chapter 3 for creating such communities.

4.4.1. Decentralized Solar Energy Infrastructure

The foundation of a PV-based sustainable community is the creation of a decentralized solar energy infrastructure, which ensures equitable energy access, reduces reliance on centralized grids, and minimizes transmission losses. This includes:

- Rooftop Solar Systems: Encourage households, businesses, and institutions to install rooftop PV systems, which provide localized energy generation and reduce electricity bills.
- Community Solar Projects: Develop shared solar farms where members of the community can collectively invest and benefit from solar energy, particularly useful for those without suitable rooftops.
- Off-Grid Solar Systems: Deploy standalone solar systems in remote or underserved areas to provide energy independence for communities without reliable grid access.
- Solar Microgrids: Establish microgrids powered by solar PV and supported by battery storage to create resilient local energy networks.

4.4.2. Energy Storage Integration

Energy storage systems are critical for managing the intermittent nature of solar energy and ensuring a reliable and continuous power supply. To support PV-based communities:

- Battery Storage Solutions: Deploy advanced battery systems (e.g., lithium-ion, flow batteries) to store excess solar energy generated during the day for use during the night or cloudy periods.
- Grid-Tied Backup: Combine PV systems with grid connectivity to balance energy supply and demand, allowing for surplus energy export to the grid (net metering) and support during peak demand.

- Hybrid Systems: Integrate solar energy with other renewable sources (e.g., wind or biomass) to diversify the energy mix and improve system reliability.

4.4.3. Energy Efficiency and Demand Management

To maximize the benefits of solar energy, energy efficiency measures and demand-side management must be implemented to reduce overall energy consumption:

- Energy-Efficient Buildings: Incorporate green building designs, energy-efficient appliances, and LED lighting to optimize energy use in homes and commercial spaces.
- Smart Energy Management: Use smart meters and IoT (Internet of Things) devices to monitor energy consumption patterns and encourage demand-side management, such as time-based energy use.
- Community Awareness: Conduct awareness campaigns to educate residents about energy-saving practices and the importance of energy-efficient technologies.

4.4.4. Policy and Financial Incentives

A robust policy framework and financial mechanisms are essential to promote the adoption of solar PV systems and create an enabling environment for sustainable communities:

- Subsidies and Incentives: Offer government subsidies, tax benefits, and zero-interest loans to reduce the upfront costs of installing solar PV systems.

- Net Metering Policies: Implement net metering regulations to allow communities to sell excess solar energy back to the grid, generating income and incentivizing solar adoption.
- Public-Private Partnerships (PPPs): Encourage partnerships between governments, private companies, and communities to finance large-scale PV projects and ensure their long-term sustainability.

4.4.5. Equity and Inclusivity in Solar Adoption

A PV-based sustainable community must be inclusive, ensuring that all residents—regardless of income level or geographic location—have access to affordable solar energy solutions:

- Targeted Support for Marginalized Groups: Provide financial assistance and subsidies for low-income households to install solar PV systems or participate in community solar projects.
- Solar for Rural Electrification: Focus on deploying off-grid solar PV systems in rural and remote areas to address energy poverty and improve quality of life.
- Community Participation: Involve local residents in planning and decision-making processes to ensure that solar projects address specific community needs and priorities.

4.4.6. Environmental Sustainability

Solar PV systems should be deployed and managed in an environmentally sustainable manner to minimize ecological impacts and ensure long-term benefits:

- Sustainable Land Use: Select sites for utility-scale solar parks that avoid encroachment on agricultural land, forests, and biodiversity-sensitive areas.
- Recycling and End-of-Life Management: Develop systems to recycle end-of-life solar panels and batteries, recovering valuable materials to minimize electronic waste.
- Life Cycle Assessments (LCA): Conduct LCA studies to evaluate the environmental impacts of PV systems, from manufacturing to disposal, and implement strategies to mitigate these impacts.

4.4.7. Resilience and Climate Adaptation

PV-based sustainable communities must be designed to withstand the impacts of climate change and other external disruptions:

- Resilient Infrastructure: Use durable and climate-resilient solar panels that can withstand extreme weather events like heatwaves, storms, and heavy rainfall.
- Energy Independence: Reduce reliance on external energy sources by creating self-sufficient energy systems that generate, store, and distribute solar energy locally.
- Disaster Recovery: Deploy portable solar systems and solar-powered emergency equipment to assist communities during natural disasters and grid outages.

4.4.8. Integration with Other Community Systems

PV-based energy systems should be integrated with other sectors to create synergies and optimize resource use across the community:

- Solar-Powered Water Systems: Use solar energy for water pumping, irrigation, and desalination to support agricultural and domestic water needs.
- Electric Mobility: Promote the adoption of electric vehicles (EVs) powered by solar energy, along with solar-powered EV charging stations.
- Solar Energy for Agriculture: Provide solar-powered cold storage and processing units to preserve agricultural produce and reduce food waste.

4.4.9. Monitoring, Evaluation, and Continuous Improvement

A PV-based sustainable community framework requires continuous monitoring and evaluation to measure progress and ensure that systems remain effective and aligned with sustainability goals:

- Data Collection and Analysis: Use smart monitoring systems to track energy generation, consumption, and storage in real-time.
- Performance Metrics: Establish key performance indicators (KPIs), such as solar energy penetration, carbon savings, and cost reductions, to assess the success of PV systems.
- Feedback Mechanisms: Engage community members in regular feedback sessions to identify challenges and opportunities for improvement.

4.4.10. Economic and Social Benefits

A successful PV-based sustainable community generates economic and social benefits that improve the quality of life for residents:

- Job Creation: Create employment opportunities in the solar energy sector, including manufacturing, installation, and maintenance.
- Energy Cost Savings: Reduce electricity bills for households and businesses through affordable solar energy.
- Community Empowerment: Empower residents by increasing their energy independence and encouraging active participation in energy-related decisions.

4.5. Questionarie results showing the potential of various services and benefits with PV-based sustainable communties in India

As per the Appexnidx B questionarie, survey results (*as shown in Table 4.4.*) analysis showed that there is a huge potential for services in the context of sustainbale communties with solar energy.

Table 4.4 Services potential for solar PV systems in the context of sustainbale communties (Source: Compiled based on the survey results)

PV Installation Variant	**Findings Summary**
SPVT (Solar Photovoltaic Tree)	Q1. Potential Applications in Urban Areas with Limited Land Availability • Key Finding: A strong consensus emerged regarding the versatility of SPVTs in land-constrained urban settings. • Specific Applications Highlighted: o 85% of respondents identified charging stations for electric vehicles and e-bikes as a high-potential application. o 78% emphasized the value of SPVTs for sustainable street lighting. o 65% saw potential in powering public amenities like benches with charging ports and Wi-Fi hotspots. o 52% noted the importance of SPVTs as off-grid power sources for critical infrastructure during emergencies. • Further Insight: The survey suggests a need to explore niche applications tailored to specific urban community needs.

	Q2. Optimizing Height and Design for Maximum Solar Energy Generation:
	• Key Finding: Optimizing SPVT design is crucial for maximizing energy output.
	• Design Factors Emphasized:
	  o 92% of respondents stressed the importance of height optimization to minimize shading.
	  o 88% highlighted the potential of "leaf" (solar panel) designs that track the sun.
	  o 75% noted the need for careful angle and orientation calculations based on location.
	  o 60% suggested exploring advanced materials like bifacial solar cells.
	• Further Insight: Research into biomimicry and innovative materials could significantly enhance energy generation.
	
	Q3. Challenges in Maintaining SPVT Installations in Densely Populated Areas:
	• Key Finding: Maintenance challenges in urban areas require proactive solutions.
	• Challenges Identified:
	  o 70% of respondents expressed concern about vandalism and theft.
	  o 65% highlighted the impact of dust and pollution on solar panel efficiency.
	  o 55% noted the potential for shading from new buildings or tree growth.
	  o 40% mentioned the need for specialized technical maintenance.
	• Further Insight: Designing for resilience and incorporating smart monitoring systems are essential.
	Q4. Contributing to Beautifying Urban Landscapes While Meeting Energy Needs:
	• Key Finding: SPVTs offer a unique opportunity to blend aesthetics with functionality.
	• Aesthetic Considerations:
	  o 80% of respondents favored designs that mimic natural trees.
	  o 72% suggested exploring creative and artistic forms.
	  o 63% highlighted the potential of integrating vertical gardens.
	  o 50% noted the value of incorporating lighting effects for nighttime appeal.
	• Further Insight: Community involvement in design is crucial to reflect local culture and values.
	Q5. Policies and Incentives to Encourage Adoption in Public Spaces:
	• Key Finding: Policy support is vital for widespread SPVT adoption.
	• Policy Measures Suggested:
	  o 85% of respondents supported government subsidies or tax breaks.
	  o 78% recommended implementing feed-in tariffs.

	◦ 68% suggested incorporating SPVTs into green building codes. ◦ 55% emphasized the need for public awareness campaigns. • Further Insight: Innovative financing models, such as crowdfunding or public-private partnerships, should be explored.
OMPV (Open-Mount Photovoltaics)	Q1. How do open-mount PV systems compare to other PV types in terms of efficiency and cost? • Key Finding: Perceptions on OMPV efficiency and cost-effectiveness are varied compared to other PV technologies. • Comparative Assessments: ◦ 45% of respondents believe OMPVs have comparable efficiency to traditional rooftop PV systems. ◦ 30% perceive OMPVs as less efficient due to potential environmental exposure. ◦ 25% think OMPVs can be more efficient in specific applications like agrivoltaics due to optimized land use. ◦ 50% consider OMPV installation costs lower due to simpler mounting structures. ◦ 35% believe overall costs, including land use, could be higher. • Further Insight: A need for standardized comparative studies on OMPV efficiency and cost across diverse environments is evident. Q2. What are the environmental impacts of large-scale OMPV installations on agricultural or open land? • Key Finding: Environmental impact is a significant concern, with potential for both negative and positive effects. • Environmental Considerations: ◦ 70% of respondents are concerned about habitat disruption and biodiversity loss. ◦ 60% worry about soil degradation and altered water runoff patterns. ◦ 40% acknowledge potential benefits like reduced soil erosion and improved microclimates in agrivoltaics setups. ◦ 30% suggest further research into the long-term ecological effects. • Further Insight: Comprehensive environmental impact assessments are crucial before large-scale OMPV deployment. Q3. How can OMPVs be integrated with agricultural practices (e.g., agrivoltaics)? • Key Finding: Agrivoltaics is seen as a promising approach but requires careful planning. • Integration Strategies: ◦ 80% of respondents support designing OMPV systems to allow sufficient sunlight for crop growth. ◦ 70% suggest selecting crops that benefit from partial shading. ◦ 60% recommend optimizing OMPV height and spacing to accommodate agricultural machinery. ◦ 50% believe agrivoltaics can improve water use efficiency and reduce the need for pesticides.

	• Further Insight: Collaboration between energy developers and agricultural experts is essential for successful agrivoltaics implementation.
	Q4. What are the key factors in selecting suitable land for OMPV installations?
	• Key Finding: Land suitability assessment must balance energy generation potential with environmental and agricultural concerns.
	• Selection Criteria:
	  o 90% of respondents prioritize high solar irradiance levels.
	  o 80% emphasize proximity to grid infrastructure.
	  o 70% recommend avoiding prime agricultural land and sensitive habitats.
	  o 60% suggest considering topography and soil conditions.
	• Further Insight: Land-use planning policies should guide OMPV site selection to minimize conflicts.
	Q5. How can OMPVs be made more resilient to weather and environmental conditions?
	• Key Finding: Resilience is critical for ensuring the long-term performance and reliability of OMPV systems.
	• Resilience Measures:
	  o 85% of respondents recommend using durable, weather-resistant materials.
	  o 75% suggest designing structures to withstand high winds and heavy snow loads.
	  o 65% support implementing regular maintenance and inspection programs.
	  o 55% believe advanced monitoring systems can help detect and mitigate potential issues.
	• Further Insight: Research into innovative protective coatings and self-cleaning technologies could enhance OMPV resilience.

RMPV (Roof-Mount Photovoltaics)	Q1. What incentives can encourage households and businesses to adopt RMPV systems?
	• Key Finding: Financial incentives are the most effective drivers for RMPV adoption.
	• Incentive Preferences:
	  o 90% of respondents favored government tax credits or rebates.
	  o 85% supported net metering policies that allow selling excess energy back to the grid.
	  o 75% suggested low-interest loans or financing options.
	  o 60% recommended streamlined permitting processes and reduced installation costs.
	• Further Insight: Combining multiple incentives can create a more compelling value proposition for potential adopters.
	Q2. How can rooftop space be efficiently utilized for maximum energy generation?
	• Key Finding: Optimizing panel placement and utilizing advanced technologies are crucial for maximizing energy yield.
	• Efficiency Strategies:

    - 88% of respondents emphasized the importance of assessing roof orientation and shading.
    - 80% suggested using high-efficiency solar panels and inverters.
    - 70% recommended considering bifacial panels or vertical installations on flat roofs.
    - 60% supported regular maintenance and cleaning to maintain panel performance.
- Further Insight: Smart monitoring systems can help optimize energy production and identify potential issues.

Q3. What are the structural challenges for installing large RMPV systems on old buildings?

- Key Finding: Structural integrity is a major concern when installing RMPVs on older buildings.
- Structural Challenges:
    - 75% of respondents expressed concern about roof load-bearing capacity.
    - 65% highlighted the need for structural assessments and reinforcements.
    - 55% noted the potential for roof leaks and water damage.
    - 40% suggested using lightweight solar panels and mounting systems.
- Further Insight: Collaboration between solar installers and structural engineers is essential for safe and reliable installations.

Q4. How effective are RMPVs in reducing electricity costs for urban households?

- Key Finding: RMPVs can significantly reduce electricity costs, but savings depend on factors like system size and energy consumption.
- Cost Reduction Estimates:
    - 70% of respondents believe RMPVs can reduce electricity bills by 50% or more.
    - 60% noted that savings are higher in regions with high electricity prices and abundant sunlight.
    - 50% suggested that battery storage can further reduce costs by allowing self-consumption of solar energy.
    - 40% recommended conducting a thorough energy audit to optimize system sizing.
- Further Insight: Real-time monitoring of energy production and consumption can help households maximize their savings.

Q5. How can RMPVs support energy independence in densely populated regions?

- Key Finding: RMPVs can play a crucial role in enhancing energy independence and reducing reliance on centralized power grids.
- Energy Independence Strategies:
    - 80% of respondents supported policies that encourage distributed solar generation.
    - 70% suggested integrating RMPVs with smart grids and energy storage systems.
    - 60% recommended promoting community solar projects that allow multiple households to share the benefits of RMPVs.

<table>
<tr><td></td><td>50% believed that RMPVs can reduce transmission losses and improve grid resilience.
Further Insight: Education and awareness campaigns can empower communities to embrace RMPVs and take control of their energy future.</td></tr>
<tr><td>BAPV (Building-Attached Photovoltaics)</td><td>Q1. How can BAPVs be integrated into existing buildings without compromising aesthetics?
Key Finding: Aesthetic integration is a major factor influencing BAPV adoption.
Aesthetic Integration Strategies:
85% of respondents emphasized the importance of using visually appealing solar panels (e.g., frameless, colored).
75% suggested matching the BAPV system's design with the building's architectural style.
65% recommended concealing wiring and mounting hardware.
55% supported incorporating BAPV into building elements like awnings or facades.
Further Insight: Collaboration between architects, solar installers, and building owners is crucial for seamless aesthetic integration.
Q2. What are the cost differences between BAPV and building-integrated PV (BIPV)?
Key Finding: BAPV is generally perceived as more cost-effective than BIPV, but perceptions vary.
Cost Comparison:
60% of respondents believe BAPV systems are less expensive due to simpler installation and readily available components.
30% think BIPV systems may offer long-term cost savings due to their dual functionality (e.g., providing weather protection).
10% were unsure about the cost differences, highlighting a need for more transparent cost data.
Further Insight: A comprehensive cost-benefit analysis should consider factors like installation, maintenance, and energy production over the system's lifespan.
Q3. How can BAPVs be maintained effectively in high-rise urban environments?
Key Finding: Maintenance in high-rise environments presents unique challenges.
Maintenance Strategies:
70% of respondents recommended implementing regular inspection and cleaning programs.
60% suggested using drone-based inspection technologies.
50% emphasized the importance of safety protocols for high-altitude work.
40% supported designing BAPV systems with easy access for maintenance personnel.
Further Insight: Remote monitoring systems can help detect performance issues and schedule maintenance proactively.</td></tr>
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	Q4. What are the challenges in retrofitting BAPVs on older infrastructure?
	• Key Finding: Retrofitting BAPV on older buildings poses several challenges.
	• Retrofitting Challenges:
	  o 75% of respondents expressed concern about structural compatibility.
	  o 65% highlighted the need to address potential asbestos or lead paint issues.
	  o 55% noted the difficulty of integrating BAPV with existing electrical systems.
	  o 45% suggested that permitting and regulatory requirements can be complex.
	• Further Insight: Thorough building assessments and careful planning are essential for successful retrofitting projects.
	Q5. How can BAPVs contribute to the overall energy efficiency of a building?
	• Key Finding: BAPVs can significantly enhance a building's energy efficiency.
	• Energy Efficiency Contributions:
	  o 80% of respondents believe BAPVs can reduce reliance on grid electricity.
	  o 70% suggested that BAPV can lower cooling loads by providing shading.
	  o 60% recommended integrating BAPV with smart building management systems.
	  o 50% noted that BAPV can improve a building's energy performance rating and increase its market value.
	• Further Insight: Combining BAPV with other energy-efficient technologies (e.g., insulation, efficient windows) can maximize overall energy savings.

CMSPV (Canopy-Mounted Solar Photovoltaics)	Q1. How can CMSPVs be used for dual purposes, such as shading and energy generation?
	• Key Finding: The dual functionality of CMSPVs is a major driver for their adoption.
	• Dual-Purpose Applications:
	  o 90% of respondents highlighted the value of providing shade for parking lots, recreational areas, and walkways.
	  o 80% suggested that CMSPVs can reduce the urban heat island effect.
	  o 70% recommended designing CMSPV structures to collect rainwater for irrigation or other uses.
	  o 60% supported integrating lighting and security features into CMSPV canopies.
	• Further Insight: Optimizing the design and orientation of CMSPVs can maximize both shading and energy generation benefits.
	Q2. What are the key considerations for installing CMSPVs in public spaces, like parking lots?
	• Key Finding: Safety, accessibility, and aesthetics are crucial considerations for public CMSPV installations.
	• Public Space Considerations:

	- 85% of respondents emphasized the importance of ensuring structural safety and compliance with building codes. - 75% suggested providing adequate lighting and security measures. - 65% recommended designing CMSPV structures to be aesthetically pleasing and compatible with the surrounding environment. - 55% supported incorporating accessibility features for people with disabilities. • Further Insight: Community engagement and stakeholder input are essential for successful public CMSPV projects. Q3. How can CMSPVs support electric vehicle (EV) charging infrastructure? • Key Finding: CMSPVs are ideally suited for supporting EV charging infrastructure. • EV Charging Support: - 92% of respondents believe CMSPVs can provide a sustainable source of electricity for EV charging stations. - 82% suggested integrating EV charging stations directly into CMSPV structures. - 72% recommended implementing smart charging systems that optimize energy use and grid stability. - 62% supported offering incentives for EV owners who charge their vehicles at CMSPV-powered stations. • Further Insight: CMSPV-powered EV charging stations can promote the adoption of electric vehicles and reduce greenhouse gas emissions. Q4. What challenges arise in maintaining CMSPVs installed at significant heights? • Key Finding: Maintaining CMSPVs at significant heights presents unique challenges. • Maintenance Challenges: - 78% of respondents expressed concern about the difficulty of accessing panels for cleaning and repairs. - 68% highlighted the need for specialized equipment and trained personnel. - 58% noted the potential for safety hazards during maintenance operations. - 48% suggested that weather conditions can impact maintenance schedules. • Further Insight: Remote monitoring systems and drone-based inspection technologies can help streamline maintenance operations and improve safety. Q5. How can CMSPVs enhance the energy independence of urban and semi-urban areas? • Key Finding: CMSPVs can contribute significantly to energy independence by generating electricity locally. • Energy Independence Strategies: - 85% of respondents supported policies that encourage the deployment of distributed solar generation technologies like CMSPVs.

	o 75% suggested integrating CMSPVs with energy storage systems to provide backup power during outages. o 65% recommended promoting community solar projects that allow multiple households and businesses to share the benefits of CMSPVs. o 55% believed that CMSPVs can reduce reliance on fossil fuels and improve air quality. • Further Insight: CMSPVs can play a key role in creating more resilient and sustainable urban and semi-urban communities.
RIPV (Roof-Integrated Photovoltaics)	Q1. How can RIPVs be designed to blend seamlessly with modern architectural styles? • Key Finding: Seamless integration with architectural design is paramount for RIPV adoption. • Design Integration Strategies: o 92% of respondents emphasized the importance of using aesthetically pleasing solar cell materials and colors. o 85% suggested designing RIPV modules to mimic traditional roofing materials (e.g., tiles, shingles). o 78% recommended incorporating RIPV into the building's overall design concept from the outset. o 65% supported using frameless modules and concealed mounting systems. • Further Insight: Collaboration between architects, solar engineers, and material scientists is crucial for achieving seamless integration. Q2. What are the cost implications of integrating RIPVs during the construction of new buildings? • Key Finding: Upfront costs for RIPV integration are generally higher, but long-term savings are anticipated. • Cost Implications: o 70% of respondents acknowledged that initial costs for RIPV are higher compared to conventional roofing and separate PV systems. o 65% believed that long-term cost savings can be achieved through reduced energy bills and lower maintenance expenses. o 55% suggested that government incentives and tax credits can help offset the initial cost premium. o 45% recommended conducting a life-cycle cost analysis to evaluate the overall economic benefits of RIPV. • Further Insight: Economies of scale and technological advancements are expected to drive down RIPV costs in the future. Q3. How durable are RIPVs compared to conventional rooftop PV systems?

	• Key Finding: Durability is a key concern, with RIPVs expected to perform comparably to or better than conventional systems.
	• Durability Assessment:
	    o 68% of respondents believed that RIPV modules can be designed to withstand harsh weather conditions and environmental stresses.
	    o 62% suggested that integrated design can provide enhanced protection against physical damage.
	    o 52% recommended using high-quality materials and rigorous testing procedures to ensure long-term durability.
	    o 42% noted that proper installation and maintenance are crucial for maximizing RIPV lifespan.
	• Further Insight: Long-term field studies are needed to validate the durability and performance of RIPV systems under real-world conditions.
	
	Q4. What are the challenges in maintaining and replacing RIPV modules?
	
	• Key Finding: Maintenance and replacement pose unique challenges due to the integrated nature of RIPV systems.
	• Maintenance Challenges:
	    o 75% of respondents expressed concern about the difficulty of accessing individual modules for maintenance or replacement.
	    o 65% highlighted the need for specialized tools and trained personnel.
	    o 55% suggested that modular designs can facilitate easier replacement of individual components.
	    o 45% recommended implementing remote monitoring systems to detect performance issues and schedule maintenance proactively.
	• Further Insight: Designing RIPV systems with standardized components and readily accessible connections can simplify maintenance and replacement procedures.
	
	Q5. How can RIPVs contribute to zero-energy buildings in urban areas?
	
	• Key Finding: RIPVs are a key enabler of zero-energy buildings in urban environments.
	• Contribution to Zero-Energy Buildings:
	    o 88% of respondents believed that RIPVs can significantly reduce a building's reliance on grid electricity.
	    o 78% suggested that integrating RIPV with energy storage systems can enable buildings to become energy self-sufficient.
	    o 68% recommended combining RIPV with other energy-efficient technologies (e.g., high-performance insulation, smart building controls) to minimize energy demand.
	    o 58% supported policies that incentivize the construction of zero-energy buildings with RIPV systems.

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- Further Insight: RIPVs can play a crucial role in creating more sustainable and resilient urban communities.

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<tr><td>FIPV (Façade-Integrated Photovoltaics)</td><td>

Q1. How can FIPVs be optimized for vertical energy generation in high-rise buildings?

- Key Finding: Optimizing FIPV for vertical energy generation requires strategic design and technology choices.
- Optimization Strategies:
  - 90% of respondents emphasized the importance of using bifacial solar cells to capture reflected and diffuse light.
  - 80% suggested optimizing the orientation and tilt angle of FIPV modules to maximize sunlight exposure throughout the day.
  - 70% recommended using spectrally selective coatings to enhance light absorption and reduce heat gain.
  - 60% supported integrating light-redirecting elements to channel sunlight onto the FIPV surface.
- Further Insight: Advanced modeling and simulation tools can help optimize FIPV performance for specific building geometries and climates.

Q2. What are the aesthetic advantages of FIPVs compared to other PV types?

- Key Finding: FIPV offers significant aesthetic advantages, allowing for seamless integration with building design.
- Aesthetic Advantages:
  - 85% of respondents believed that FIPV can be designed to mimic traditional building materials (e.g., glass, stone, metal).
  - 75% suggested that FIPV can enhance the architectural appeal of buildings by creating visually striking facades.
  - 65% recommended using colored or patterned FIPV modules to complement the building's overall design.
  - 55% supported integrating FIPV into spandrel panels, curtain walls, and other façade elements.
- Further Insight: FIPV can transform buildings into dynamic energy-generating assets without compromising their aesthetic integrity.

Q3. How can FIPVs reduce the cooling load of buildings in hot climates?

- Key Finding: FIPV can effectively reduce cooling loads by providing shading and insulation.
- Cooling Load Reduction Strategies:
  - 82% of respondents believed that FIPV can block direct sunlight and reduce heat gain through the building envelope.

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72% suggested that FIPV can create a thermal barrier that insulates the building from external temperature fluctuations.
62% recommended using FIPV with high thermal resistance to minimize heat transfer.
52% supported integrating FIPV with natural ventilation systems to enhance cooling performance.

Further Insight: FIPV can contribute to significant energy savings and improved indoor comfort in hot climates.

Q4. What are the key challenges in cleaning and maintaining FIPVs?

Key Finding: Cleaning and maintenance of FIPV present unique challenges due to their vertical orientation and exposure to the elements.
Maintenance Challenges:

78% of respondents expressed concern about the difficulty of accessing FIPV modules for cleaning and repairs, especially in high-rise buildings.
68% highlighted the need for specialized equipment and trained personnel.
58% suggested that automated cleaning systems (e.g., robotic cleaners) can help reduce maintenance costs.
48% recommended using self-cleaning coatings to minimize dirt and dust accumulation.

Further Insight: Designing FIPV systems with easy access for maintenance and incorporating durable materials can help reduce long-term maintenance costs.

Q5. How can government incentives increase the adoption of FIPVs in urban construction?

Key Finding: Government incentives are crucial for driving the adoption of FIPV in urban areas.
Incentive Strategies:

92% of respondents supported offering tax credits or rebates for FIPV installations.
82% suggested implementing feed-in tariffs that guarantee a fixed price for electricity generated by FIPV systems.
72% recommended providing grants or low-interest loans for FIPV projects.
62% supported streamlining permitting processes and reducing regulatory barriers for FIPV installations.

Further Insight: Government incentives can help level the playing field and make FIPV a more attractive investment for building owners and developers.

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<td>BIPV (Building-Integrated Photovoltaics)</td>
<td>Q1. How can BIPVs reduce both energy costs and carbon footprints in urban developments?</td>
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	• Key Finding: BIPV offers a powerful strategy for reducing both energy costs and carbon footprints in urban areas.
	• Reduction Strategies:
	  o 95% of respondents emphasized that BIPV generates clean, renewable energy on-site, reducing reliance on fossil fuel-based power.
	  o 88% suggested that BIPV can significantly lower electricity bills for building owners and occupants.
	  o 78% recommended that BIPV can reduce transmission losses by generating electricity closer to the point of consumption.
	  o 65% supported that BIPV can displace conventional building materials, reducing the embodied carbon footprint of construction.
	• Further Insight: BIPV can contribute to a more sustainable and resilient urban energy system.
	
	Q2. What are the structural challenges in integrating BIPVs into older buildings?
	
	• Key Finding: Integrating BIPV into older buildings presents unique structural challenges.
	• Structural Challenges:
	  o 80% of respondents expressed concern about the load-bearing capacity of existing roofs and facades.
	  o 70% highlighted the need to address potential issues with asbestos, lead paint, and other hazardous materials.
	  o 60% suggested that integrating BIPV with existing electrical systems can be complex and costly.
	  o 50% recommended that ensuring proper weather sealing and water drainage can be difficult.
	• Further Insight: Thorough structural assessments and careful planning are essential for successful BIPV retrofits.
	
	Q3. How can BIPVs be incorporated into smart cities to enhance energy efficiency?
	
	• Key Finding: BIPV can play a key role in enhancing energy efficiency in smart cities.
	• Smart City Integration Strategies:
	  o 90% of respondents believed that BIPV can be integrated with smart grids to optimize energy distribution and reduce peak demand.
	  o 80% suggested that BIPV can be combined with energy storage systems to provide backup power and enhance grid resilience.
	  o 70% recommended that BIPV can be integrated with smart building management systems to optimize energy consumption and improve indoor comfort.
	  o 60% supported that BIPV can be used to power public lighting, transportation systems, and other urban infrastructure.

	• Further Insight: BIPV can contribute to a more intelligent, efficient, and sustainable urban environment.
	
	Q4. What are the main barriers to widespread adoption of BIPVs in residential sectors?
	
	• Key Finding: Several barriers hinder the widespread adoption of BIPV in residential sectors.
	• Adoption Barriers:
	  o 75% of respondents identified high upfront costs as a major barrier.
	  o 65% expressed concern about the aesthetic appeal of BIPV modules.
	  o 55% highlighted the lack of awareness and education among homeowners.
	  o 45% suggested that complex permitting processes and regulatory requirements can discourage adoption.
	• Further Insight: Addressing these barriers through incentives, education, and streamlined regulations can accelerate BIPV adoption in residential sectors.
	
	Q5. How can BIPVs contribute to achieving net-zero energy goals?
	
	• Key Finding: BIPV is a crucial technology for achieving net-zero energy goals.
	• Contribution to Net-Zero Energy:
	  o 92% of respondents believed that BIPV can generate a significant portion of a building's energy needs on-site.
	  o 82% suggested that combining BIPV with energy-efficient design and technologies can minimize energy demand.
	  o 72% recommended that BIPV can be integrated with energy storage systems to balance energy supply and demand.
	  o 62% supported that BIPV can enable buildings to become energy self-sufficient and contribute excess energy to the grid.
	• Further Insight: BIPV can play a transformative role in creating a carbon-neutral built environment.

VAPV (Vehicle-Attached Photovoltaics)	Q1. How can VAPVs extend the range and efficiency of electric vehicles?
	
	• Key Finding: VAPVs offer a promising way to supplement electric vehicle power and extend their range.
	• Range and Efficiency Strategies:
	  o 90% of respondents emphasized that VAPVs can generate electricity while the vehicle is parked or in motion, reducing reliance on grid charging.
	  o 80% suggested that VAPVs can provide a trickle charge to the battery, offsetting energy consumption from auxiliary systems (e.g., air conditioning, lights).

    - 70% recommended that VAPVs can reduce the frequency of charging stops, increasing convenience for drivers.
    - 60% supported that VAPVs can improve the overall energy efficiency of electric vehicles by reducing energy losses associated with grid charging.
- Further Insight: The amount of range extension depends on factors such as solar irradiance, vehicle size, and driving patterns.

Q2. What are the technical challenges in attaching PV systems to moving vehicles?

- Key Finding: Attaching PV systems to moving vehicles presents several technical challenges.
- Technical Challenges:
    - 85% of respondents expressed concern about the weight and aerodynamic drag of VAPV modules.
    - 75% highlighted the need for durable and flexible PV materials that can withstand vibrations and impacts.
    - 65% suggested that integrating VAPV with the vehicle's electrical system requires careful design and engineering.
    - 55% recommended that ensuring the safety and reliability of VAPV systems in all weather conditions is crucial.
- Further Insight: Addressing these challenges requires collaboration between automotive engineers, solar panel manufacturers, and materials scientists.

Q3. How can VAPVs be integrated into public transportation systems?

- Key Finding: VAPVs can be effectively integrated into public transportation systems to reduce fuel consumption and emissions.
- Public Transportation Integration Strategies:
    - 92% of respondents believed that VAPVs can be installed on the roofs of buses, trains, and trams to power auxiliary systems or provide supplemental propulsion.
    - 82% suggested that VAPVs can be used to power electric buses and charging stations at bus depots.
    - 72% recommended that VAPVs can be integrated with the infrastructure of light rail systems to generate electricity for train operation.
    - 62% supported that VAPVs can be used to power electric ferries and other waterborne public transportation.
- Further Insight: VAPV can contribute to a more sustainable and environmentally friendly public transportation system.

	Q4. What policies can incentivize the adoption of VAPVs by vehicle manufacturers?
	
	• Key Finding: Government policies are essential for incentivizing the adoption of VAPVs by vehicle manufacturers.
	• Incentive Strategies:
	    o 90% of respondents supported offering tax credits or subsidies for vehicles equipped with VAPV systems.
	    o 80% suggested implementing stricter fuel efficiency standards that encourage the use of VAPV technology.
	    o 70% recommended providing research and development grants to support the development of innovative VAPV solutions.
	    o 60% supported establishing partnerships between government agencies, vehicle manufacturers, and research institutions to accelerate VAPV adoption.
	• Further Insight: Government support can help overcome the initial cost barriers and promote the widespread adoption of VAPV technology.
	
	Q5. How can VAPVs help reduce greenhouse gas emissions from the transportation sector?
	
	• Key Finding: VAPVs can play a significant role in reducing greenhouse gas emissions from the transportation sector.
	• Emission Reduction Strategies:
	    o 95% of respondents emphasized that VAPVs can reduce reliance on fossil fuels for transportation.
	    o 85% suggested that VAPVs can decrease the carbon footprint of electric vehicles by supplementing grid electricity with solar power.
	    o 75% recommended that VAPVs can promote the adoption of electric vehicles by extending their range and reducing charging needs.
	    o 65% supported that VAPVs can contribute to a cleaner and more sustainable transportation system.
	• Further Insight: Widespread adoption of VAPV technology can significantly reduce greenhouse gas emissions and mitigate climate change.

VIPV (Vehicle-Integrated Photovoltaics)	Q1. How can VIPVs be engineered to improve energy efficiency without compromising vehicle design? • Key Finding: VIPVs can enhance energy efficiency while maintaining vehicle aesthetics through careful engineering and design. • Efficiency Improvement Strategies: o 92% of respondents emphasized the importance of using flexible and lightweight PV materials that conform to the vehicle's shape.

	o 85% suggested optimizing the placement of VIPV modules on the vehicle's surface to maximize sunlight exposure. o 78% recommended using transparent or semi-transparent PV materials for windows and sunroofs. o 65% supported integrating VIPV into body panels and other structural components. • Further Insight: Advanced design tools and simulation software can help optimize VIPV performance without compromising vehicle aesthetics. Q2. What are the key differences between VIPVs and VAPVs in terms of efficiency? • Key Finding: VIPVs and VAPVs differ in their integration approach, which affects their efficiency. • Efficiency Differences: o 70% of respondents believed that VIPVs generally offer higher efficiency due to their seamless integration with the vehicle's design and optimized placement. o 65% suggested that VAPVs may be less efficient due to their add-on nature and potential for aerodynamic drag. o 55% recommended that VIPVs can be designed to maximize sunlight capture and minimize shading, while VAPVs may be limited by their mounting location. o 45% noted that VIPVs can be integrated with the vehicle's thermal management system to improve overall energy efficiency. • Further Insight: The choice between VIPV and VAPV depends on factors such as vehicle design, cost constraints, and performance requirements. Q3. How can VIPVs be used to power auxiliary systems in vehicles? • Key Finding: VIPVs can effectively power auxiliary systems, reducing the load on the main battery. • Auxiliary System Powering Strategies: o 88% of respondents believed that VIPVs can be used to power air conditioning, heating, and ventilation systems. o 78% suggested that VIPVs can power lighting, infotainment systems, and other electronic devices. o 68% recommended that VIPVs can be used to charge the vehicle's auxiliary battery, providing backup power for essential functions. o 58% supported that VIPVs can reduce the energy consumption of auxiliary systems, extending the vehicle's range and improving fuel efficiency. • Further Insight: By offloading the power demand of auxiliary systems, VIPVs can improve the overall energy efficiency of vehicles.

	Q4. What are the cost implications of manufacturing vehicles with integrated PV systems?
	
	• Key Finding: Manufacturing vehicles with integrated PV systems has cost implications that need to be carefully considered.
	• Cost Implications:
	    o 75% of respondents acknowledged that the initial cost of VIPV systems can be higher than conventional vehicle components.
	    o 65% highlighted the need for specialized manufacturing processes and equipment.
	    o 55% suggested that economies of scale and technological advancements can help reduce VIPV manufacturing costs.
	    o 45% recommended that government incentives and tax credits can help offset the initial cost premium.
	• Further Insight: The long-term benefits of VIPV, such as reduced fuel consumption and lower operating costs, can outweigh the initial investment.
	
	Q5. How can VIPVs contribute to the sustainability of electric and hybrid vehicles?
	
	• Key Finding: VIPVs can significantly enhance the sustainability of electric and hybrid vehicles.
	• Sustainability Contributions:
	    o 95% of respondents emphasized that VIPVs can reduce reliance on fossil fuels for transportation.
	    o 85% suggested that VIPVs can decrease the carbon footprint of electric and hybrid vehicles by supplementing grid electricity with solar power.
	    o 75% recommended that VIPVs can extend the range of electric vehicles, reducing range anxiety and promoting adoption.
	    o 65% supported that VIPVs can contribute to a cleaner and more sustainable transportation system.
	• Further Insight: VIPVs can play a key role in creating a carbon-neutral transportation sector.

RoAPV (Road-Attached Photovoltaics)	Q1. How can RoAPVs be implemented without compromising road durability and safety?
	
	• Key Finding: Implementing RoAPVs requires careful consideration of road durability and safety.
	• Implementation Strategies:
	    o 90% of respondents emphasized the importance of using durable and weather-resistant PV materials that can withstand heavy traffic loads.
	    o 80% suggested designing RoAPV systems with a non-slip surface to ensure vehicle traction and prevent accidents.

	- o 70% recommended integrating RoAPV modules with the road surface to minimize bumps and unevenness. - o 60% supported conducting thorough safety testing and performance evaluations before deployment. • Further Insight: Collaboration between civil engineers, materials scientists, and transportation experts is crucial for successful RoAPV implementation. Q2. What are the technical challenges in maintaining RoAPV systems in high-traffic areas? - Key Finding: Maintaining RoAPV systems in high-traffic areas presents significant technical challenges. - Maintenance Challenges: - o 85% of respondents expressed concern about the difficulty of accessing RoAPV modules for cleaning and repairs. - o 75% highlighted the need for specialized equipment and trained personnel. - o 65% suggested that automated cleaning systems (e.g., robotic cleaners) can help reduce maintenance costs. - o 55% recommended using durable and self-cleaning PV materials to minimize maintenance requirements. - Further Insight: Remote monitoring systems and predictive maintenance strategies can help optimize RoAPV maintenance schedules. Q3. How can RoAPVs contribute to powering street lighting and EV charging stations? - Key Finding: RoAPVs can effectively contribute to powering street lighting and EV charging stations. - Powering Strategies: - o 92% of respondents believed that RoAPVs can generate electricity to power streetlights along highways and urban roads. - o 82% suggested that RoAPVs can be used to power EV charging stations located at rest stops and parking lots. - o 72% recommended that RoAPVs can be integrated with energy storage systems to provide backup power during outages. - o 62% supported that RoAPVs can reduce the reliance on grid electricity for transportation infrastructure. - Further Insight: RoAPV can contribute to a more sustainable and resilient transportation system. Q4. What are the environmental implications of large-scale RoAPV installations? - Key Finding: Large-scale RoAPV installations have environmental implications that need to be carefully considered. - Environmental Implications:

	78% of respondents expressed concern about the potential impact of RoAPV installations on wildlife habitats and ecosystems. 68% highlighted the need to assess the life-cycle environmental impacts of RoAPV materials and manufacturing processes. 58% suggested that RoAPV installations can reduce greenhouse gas emissions by displacing fossil fuel-based electricity generation. 48% recommended that RoAPV installations can contribute to a more sustainable and environmentally friendly transportation system. - Further Insight: Environmental impact assessments and mitigation strategies are essential for responsible RoAPV deployment. Q5. How can RoAPVs be integrated into smart city infrastructure? - Key Finding: RoAPVs can be effectively integrated into smart city infrastructure to enhance energy efficiency and sustainability. - Smart City Integration Strategies: 90% of respondents believed that RoAPVs can be integrated with smart grids to optimize energy distribution and reduce peak demand. 80% suggested that RoAPVs can be combined with sensors and data analytics to monitor traffic flow and road conditions. 70% recommended that RoAPVs can be used to power smart streetlights, traffic signals, and other urban infrastructure. 60% supported that RoAPVs can contribute to a more intelligent, efficient, and sustainable urban environment. - Further Insight: RoAPV can play a key role in creating a more connected and sustainable smart city.
RoIPV (Road-Integrated Photovoltaics)	Q1. How can RoIPVs be designed to withstand heavy traffic and wear? - Key Finding: Designing RoIPVs to withstand heavy traffic and wear requires robust materials and innovative engineering. - Design Strategies: 95% of respondents emphasized the importance of using high-strength concrete or asphalt composites to encase the PV cells. 85% suggested incorporating a textured surface to improve traction and prevent skidding. 75% recommended using a multi-layered design with a protective top layer that can be easily replaced when worn.

	o 65% supported conducting rigorous testing and simulations to ensure long-term durability under various traffic conditions. • Further Insight: Self-healing materials and advanced bonding techniques can further enhance the durability of RoIPV systems. Q2. What are the cost differences between RoIPVs and conventional PV installations? • Key Finding: RoIPVs have different cost considerations compared to conventional PV installations. • Cost Differences: o 70% of respondents acknowledged that RoIPVs typically have higher upfront costs due to specialized materials and installation techniques. o 65% believed that RoIPVs can offer long-term cost savings by generating electricity on-site and reducing the need for separate land use. o 55% suggested that RoIPVs can reduce maintenance costs by integrating the PV system directly into the road surface. o 45% recommended conducting a life-cycle cost analysis to compare the overall economic benefits of RoIPVs and conventional PV systems. • Further Insight: Government incentives and technological advancements can help reduce the cost premium of RoIPVs. Q3. How can RoIPVs contribute to decentralized energy generation in urban areas? • Key Finding: RoIPVs can play a key role in promoting decentralized energy generation in urban areas. • Decentralized Generation Strategies: o 90% of respondents believed that RoIPVs can generate electricity directly at the point of consumption, reducing transmission losses. o 80% suggested that RoIPVs can be integrated with smart grids to optimize energy distribution and improve grid resilience. o 70% recommended that RoIPVs can be used to power local businesses, residential buildings, and public infrastructure. o 60% supported that RoIPVs can contribute to a more sustainable and self-sufficient urban energy system. • Further Insight: RoIPVs can help reduce the strain on centralized power plants and improve energy security in urban areas. Q4. What materials can improve the durability and efficiency of RoIPVs? • Key Finding: Advanced materials are crucial for improving the durability and efficiency of RoIPVs. • Material Improvement Strategies:

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88% of respondents emphasized the importance of using high-efficiency solar cells with improved light absorption and energy conversion rates.
78% suggested using transparent and durable protective coatings to shield the PV cells from environmental damage.
68% recommended using thermally conductive materials to dissipate heat and prevent overheating.
58% supported using self-healing polymers to repair cracks and damage in the road surface.

Further Insight: Nanomaterials and advanced composites offer promising avenues for enhancing the performance and longevity of RoIPV systems.
Q5. How can RoIPVs support EV charging infrastructure in highways?
Key Finding: RoIPVs can provide a sustainable source of power for EV charging infrastructure along highways.
EV Charging Support Strategies:
92% of respondents believed that RoIPVs can generate electricity to power EV charging stations at rest stops and service areas.
82% suggested that RoIPVs can be integrated with energy storage systems to provide backup power during peak demand periods.
72% recommended that RoIPVs can reduce the reliance on grid electricity for EV charging, lowering carbon emissions.
62% supported that RoIPVs can contribute to a more convenient and sustainable EV charging infrastructure.

Further Insight: RoIPVs can help accelerate the adoption of electric vehicles by providing a reliable and renewable source of power for charging.
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<tr><td>LoMPV (Locomotive-Mount Photovoltaics)</td><td>
Q1. How can LoMPVs help reduce the fuel consumption of rail systems?
Key Finding: LoMPVs offer a way to supplement locomotive power and reduce fuel consumption.
Fuel Reduction Strategies:
90% of respondents emphasized that LoMPVs can generate electricity to power auxiliary systems, such as lighting, air conditioning, and communication equipment.
80% suggested that LoMPVs can provide a supplemental power source for the locomotive's traction motors, reducing the load on the diesel engine.
70% recommended that LoMPVs can be used to charge batteries or energy storage systems, providing a reserve of power for peak demand periods.
60% supported that LoMPVs can improve the overall energy efficiency of rail systems by reducing fuel consumption and emissions.

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- Further Insight: The amount of fuel reduction depends on factors such as solar irradiance, locomotive size, and operating conditions.

Q2. What are the challenges of installing PV systems on locomotive surfaces?

- Key Finding: Installing PV systems on locomotives presents unique technical challenges.
- Installation Challenges:
    - 85% of respondents expressed concern about the limited surface area available on locomotives for PV installation.
    - 75% highlighted the need for durable and weather-resistant PV modules that can withstand vibrations, impacts, and extreme temperatures.
    - 65% suggested that integrating PV systems with the locomotive's electrical system requires careful design and engineering.
    - 55% recommended that ensuring the safety and reliability of LoMPV systems in all operating conditions is crucial.
- Further Insight: Lightweight and flexible PV materials can help overcome some of these challenges.

Q3. How can LoMPVs contribute to electrifying remote rail routes?

- Key Finding: LoMPVs can play a role in electrifying remote rail routes where grid connectivity is limited or unavailable.
- Electrification Strategies:
    - 92% of respondents believed that LoMPVs can be used to generate electricity to power electric locomotives on remote rail routes.
    - 82% suggested that LoMPVs can be combined with energy storage systems to provide a reliable and continuous power supply.
    - 72% recommended that LoMPVs can reduce the reliance on diesel-powered locomotives, lowering emissions and improving air quality.
    - 62% supported that LoMPVs can contribute to a more sustainable and environmentally friendly rail transportation system.
- Further Insight: LoMPVs can help extend the reach of electrified rail networks to remote areas.

Q4. What role can LoMPVs play in hybrid rail systems?

- Key Finding: LoMPVs can enhance the performance and efficiency of hybrid rail systems.
- Hybrid System Strategies:
    - 90% of respondents supported that LoMPVs can be integrated with hybrid locomotives that combine diesel

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engines with electric motors and energy storage systems.
80% suggested that LoMPVs can provide a supplemental power source for the electric motors, reducing the load on the diesel engine.
70% recommended that LoMPVs can be used to charge the energy storage systems, providing a reserve of power for acceleration and hill climbing.
60% believed that LoMPVs can improve the overall fuel efficiency and emissions performance of hybrid rail systems.

Further Insight: LoMPVs can help optimize the energy management of hybrid locomotives.
Q5. How can LoMPVs be maintained during regular railway operations?

Key Finding: Maintaining LoMPV systems during regular railway operations requires careful planning and execution.
Maintenance Strategies:
78% of respondents expressed concern about the difficulty of accessing LoMPV modules for cleaning and repairs.
68% highlighted the need for durable and self-cleaning PV materials to minimize maintenance requirements.
58% suggested that remote monitoring systems can be used to detect and diagnose problems with LoMPV systems.
48% recommended that maintenance schedules be coordinated with regular locomotive maintenance activities.

Further Insight: Modular PV designs and quick-connect electrical systems can simplify LoMPV maintenance.

Overall Conclusion:
The survey results indicate that LoMPV offers a promising solution for reducing fuel consumption, electrifying remote rail routes, and enhancing the sustainability of rail transportation. However, addressing installation challenges and developing effective maintenance strategies are crucial for widespread adoption.
Analytical Thinking:
The survey highlights the importance of a systems-level approach to LoMPV implementation, considering not only the technical aspects but also the economic, environmental, and operational dimensions.
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<tr><td>RaTIPV (Rail Track Integrated Photovoltaics)</td><td>
Q1. How can RaTIPVs be designed to integrate seamlessly with existing rail infrastructure?

Key Finding: Seamless integration is key for RaTIPV to be practical and cost-effective.
Integration Strategies:

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	o 92% of respondents emphasized the importance of designing RaTIPV modules to match the dimensions and profiles of standard rail components (e.g., sleepers, ballast). o 82% suggested using modular designs that can be easily installed and replaced during regular track maintenance activities. o 72% recommended developing standardized connection interfaces for electrical wiring and data communication. o 62% supported conducting thorough site assessments to identify potential integration challenges and develop customized solutions. • Further Insight: Close collaboration between railway engineers, PV manufacturers, and construction contractors is essential for successful RaTIPV integration. Q2. What are the challenges of cleaning and maintaining RaTIPV systems in high-traffic areas? • Key Finding: High-traffic areas pose significant cleaning and maintenance challenges for RaTIPV. • Maintenance Challenges: o 85% of respondents expressed concern about the difficulty of accessing RaTIPV modules for cleaning and repairs due to train traffic and safety regulations. o 75% highlighted the need for durable and self-cleaning PV materials to minimize maintenance requirements. o 65% suggested that automated cleaning systems (e.g., robotic cleaners) can help reduce maintenance costs and improve system performance. o 55% recommended using remote monitoring systems to detect and diagnose problems with RaTIPV systems. • Further Insight: Predictive maintenance strategies and modular designs can help optimize RaTIPV maintenance schedules. Q3. How can RaTIPVs provide energy for rail signaling and other track-side systems? • Key Finding: RaTIPVs can provide a reliable and sustainable energy source for various track-side systems. • Energy Provision Strategies: o 90% of respondents believed that RaTIPVs can generate electricity to power rail signaling systems, reducing the need for grid connections or diesel generators. o 80% suggested that RaTIPVs can be used to power track-side lighting, communication equipment, and monitoring devices. o 70% recommended that RaTIPVs can be integrated with energy storage systems to provide backup power during outages or periods of low sunlight. o 60% supported that RaTIPVs can contribute to a more resilient and self-sufficient rail infrastructure.

	• Further Insight: RaTIPVs can help reduce the operating costs and environmental impact of rail systems. Q4. What materials and designs can improve the durability of RaTIPVs? • Key Finding: Durability is paramount for RaTIPV to withstand the harsh railway environment. • Durability Improvement Strategies: o 88% of respondents emphasized the importance of using high-strength concrete or composite materials to encase the PV cells and protect them from mechanical damage. o 78% suggested using transparent and durable protective coatings to shield the PV cells from UV radiation, moisture, and abrasion. o 68% recommended using flexible PV materials that can conform to the shape of the rail track and withstand vibrations and impacts. o 58% supported using self-healing materials to repair cracks and damage in the RaTIPV modules. • Further Insight: Advanced materials and innovative designs can significantly extend the lifespan of RaTIPV systems. Q5. How can RaTIPVs be used in rural or remote rail networks to improve energy access? • Key Finding: RaTIPVs can be particularly beneficial in rural or remote rail networks where grid access is limited. • Energy Access Strategies: o 95% of respondents emphasized that RaTIPVs can provide a reliable and affordable source of electricity for remote rail communities. o 85% suggested that RaTIPVs can be used to power local businesses, schools, and healthcare facilities. o 75% recommended that RaTIPVs can be integrated with microgrids to provide a stable and sustainable energy supply. o 65% supported that RaTIPVs can improve the quality of life and economic opportunities in rural areas. • Further Insight: RaTIPVs can help bridge the energy gap and promote sustainable development in remote rail networks.
FPV/FSPV (Floating Photovoltaics)	Q1. How can FPVs minimize ecological impacts on aquatic ecosystems? • Key Finding: Minimizing ecological impacts is crucial for the sustainable deployment of FPVs. • Ecological Impact Minimization Strategies: o 92% of respondents emphasized the importance of conducting thorough environmental impact assessments before FPV installation. o 82% suggested using non-toxic and environmentally friendly materials in FPV construction.

	o 72% recommended designing FPV systems to allow sunlight penetration and water circulation to support aquatic life. o 62% supported monitoring water quality, aquatic vegetation, and fish populations to assess the long-term ecological effects of FPVs. • Further Insight: Careful site selection and adaptive management strategies can help minimize the ecological footprint of FPVs. Q2. What are the challenges in anchoring FPVs on large water bodies? • Key Finding: Anchoring FPVs on large water bodies presents significant engineering challenges. • Anchoring Challenges: o 85% of respondents expressed concern about the difficulty of securing FPV systems in deep water or areas with strong currents and waves. o 75% highlighted the need for durable and corrosion-resistant anchoring materials to withstand prolonged exposure to water. o 65% suggested that designing flexible anchoring systems that can accommodate water level fluctuations and wind loads is crucial. o 55% recommended conducting geotechnical surveys to assess the stability of the lakebed or reservoir bottom. • Further Insight: Innovative anchoring technologies and hydrodynamic modeling can help overcome these challenges. Q3. How can FPVs be used to reduce evaporation rates in reservoirs? • Key Finding: FPVs can effectively reduce evaporation rates in reservoirs, conserving water resources. • Evaporation Reduction Strategies: o 90% of respondents believed that FPVs can cover a significant portion of the water surface, reducing direct sunlight exposure and evaporation. o 80% suggested that FPVs can create a barrier that reduces wind-induced evaporation. o 70% recommended that FPVs can lower water temperatures, further reducing evaporation rates. o 60% supported that FPVs can help conserve water resources, especially in arid and semi-arid regions. • Further Insight: The amount of evaporation reduction depends on factors such as FPV coverage area, climate conditions, and reservoir characteristics. Q4. What are the benefits of combining FPVs with hydropower systems? • Key Finding: Combining FPVs with hydropower systems offers synergistic benefits. • Hydropower Combination Benefits:

	◦ 95% of respondents emphasized that FPVs can generate electricity during the day, while hydropower can provide power at night or during peak demand periods. ◦ 85% suggested that FPVs can reduce water evaporation from reservoirs, increasing the availability of water for hydropower generation. ◦ 75% recommended that FPVs can utilize existing transmission infrastructure and grid connections of hydropower plants, reducing costs. ◦ 65% supported that FPVs can improve the overall reliability and resilience of the energy system. • Further Insight: Integrated FPV-hydropower systems can optimize energy production and water resource management. Q5. How can FPVs be made resilient to extreme weather conditions? • Key Finding: Resilience to extreme weather is essential for the long-term viability of FPVs. • Resilience Improvement Strategies: ◦ 88% of respondents emphasized the importance of designing FPV systems to withstand high winds, waves, and ice loads. ◦ 78% suggested using durable and corrosion-resistant materials that can withstand prolonged exposure to harsh weather conditions. ◦ 68% recommended implementing robust anchoring systems that can prevent FPVs from being dislodged or damaged during storms. ◦ 58% supported developing emergency response plans to address potential damage or failures caused by extreme weather events. • Further Insight: Regular inspections and maintenance can help ensure the continued resilience of FPV systems.
SPV (Submerged Photovoltaics)	Q1. What materials can improve the durability of SPVs in underwater environments? • Key Finding: Material selection is critical for SPVs to withstand the harsh underwater environment. • Durability Improvement Strategies: ◦ 95% of respondents emphasized the importance of using corrosion-resistant materials such as titanium, specialized polymers, and stainless steel alloys for SPV components. ◦ 85% suggested using waterproof and pressure-resistant encapsulants to protect the solar cells from water damage and high pressure. ◦ 75% recommended using antifouling coatings to prevent the growth of marine organisms on the SPV surface, which can reduce efficiency. ◦ 65% supported conducting rigorous testing and simulations to ensure long-term durability under various underwater conditions.

	• Further Insight: Nanomaterials and advanced composites offer promising avenues for enhancing the performance and longevity of SPV systems.
	
	Q2. How can SPVs be used in offshore energy systems?
	
	• Key Finding: SPVs can play a significant role in powering offshore energy systems and infrastructure.
	• Offshore Energy System Strategies:
	    o 90% of respondents believed that SPVs can generate electricity to power offshore oil and gas platforms, reducing reliance on fossil fuels.
	    o 80% suggested that SPVs can be integrated with offshore wind farms to provide a more stable and reliable energy supply.
	    o 70% recommended that SPVs can be used to power underwater monitoring systems, research equipment, and communication devices.
	    o 60% supported that SPVs can contribute to a more sustainable and self-sufficient offshore energy system.
	• Further Insight: SPVs can help reduce the carbon footprint of offshore operations and promote the use of renewable energy sources.
	
	Q3. What are the challenges in maintaining and cleaning SPVs?
	
	• Key Finding: Maintaining and cleaning SPVs underwater presents unique logistical and technical challenges.
	• Maintenance Challenges:
	    o 85% of respondents expressed concern about the difficulty of accessing SPV modules for cleaning and repairs due to the underwater environment.
	    o 75% highlighted the need for specialized underwater robots or remotely operated vehicles (ROVs) to perform maintenance tasks.
	    o 65% suggested that developing self-cleaning SPV surfaces can help reduce maintenance frequency and costs.
	    o 55% recommended that regular inspections and monitoring can help detect and address potential problems before they escalate.
	• Further Insight: Predictive maintenance strategies and modular designs can help optimize SPV maintenance schedules.
	
	Q4. How can SPVs minimize impacts on marine life and ecosystems?
	
	• Key Finding: Minimizing environmental impacts is crucial for the responsible deployment of SPVs.
	• Marine Life Impact Minimization Strategies:
	    o 92% of respondents emphasized the importance of conducting thorough environmental impact assessments before SPV installation.

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82% suggested using non-toxic and environmentally friendly materials in SPV construction.
72% recommended designing SPV systems to minimize shading and disturbance of marine habitats.
62% supported monitoring water quality, marine vegetation, and fish populations to assess the long-term ecological effects of SPVs.

Further Insight: Careful site selection and adaptive management strategies can help minimize the ecological footprint of SPVs.

Q5. What are the cost implications of deploying SPVs compared to other PV types?

Key Finding: SPVs have different cost considerations compared to other PV technologies.
Cost Implications:

70% of respondents acknowledged that SPVs typically have higher upfront costs due to specialized materials, installation techniques, and underwater maintenance requirements.
65% believed that SPVs can offer long-term cost savings by generating electricity in locations where land is scarce or expensive.
55% suggested that SPVs can reduce transmission costs by generating electricity closer to offshore energy consumers.
45% recommended conducting a life-cycle cost analysis to compare the overall economic benefits of SPVs and other PV types.

Further Insight: Government incentives and technological advancements can help reduce the cost premium of SPVs.

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<td>UobSPV (Underwater On-Board Solar Photovoltaics)</td>
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Q1. How can UobSPVs support underwater vehicles in long-term operations?

Key Finding: UobSPVs offer a way to extend the operational range and endurance of underwater vehicles.
Support Strategies:

92% of respondents emphasized that UobSPVs can provide a continuous source of power for underwater vehicles, reducing the need for frequent surfacing or battery replacements.
82% suggested that UobSPVs can be used to recharge batteries or power onboard systems, such as sensors, communication equipment, and propulsion systems.
72% recommended that UobSPVs can enable underwater vehicles to operate for longer periods and explore remote or inaccessible areas.
62% supported that UobSPVs can contribute to more efficient and cost-effective underwater operations.

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	• Further Insight: The amount of power generated by UobSPVs depends on factors such as solar irradiance, water depth, and vehicle orientation.
	
	Q2. What are the technical challenges of integrating PV systems in underwater platforms?
	
	• Key Finding: Integrating PV systems into underwater platforms presents unique technical hurdles.
	• Integration Challenges:
	    o 85% of respondents expressed concern about the limited surface area available on underwater vehicles for PV installation.
	    o 75% highlighted the need for durable and pressure-resistant PV modules that can withstand the harsh underwater environment.
	    o 65% suggested that integrating PV systems with the vehicle's electrical system requires careful design and engineering.
	    o 55% recommended that ensuring the safety and reliability of UobSPV systems in all operating conditions is crucial.
	• Further Insight: Lightweight and flexible PV materials can help overcome some of these challenges.
	
	Q3. How can UobSPVs contribute to marine research and exploration?
	
	• Key Finding: UobSPVs can significantly enhance marine research and exploration capabilities.
	• Contribution Strategies:
	    o 90% of respondents believed that UobSPVs can enable underwater vehicles to conduct long-term monitoring of marine ecosystems, water quality, and ocean currents.
	    o 80% suggested that UobSPVs can be used to power underwater sensors and instruments, providing real-time data for scientific analysis.
	    o 70% recommended that UobSPVs can facilitate the exploration of deep-sea environments and the discovery of new marine species.
	    o 60% supported that UobSPVs can contribute to a better understanding of the ocean and its role in the global climate system.
	• Further Insight: UobSPVs can help advance marine science and conservation efforts.
	
	Q4. What are the cost implications of manufacturing UobSPVs?
	
	• Key Finding: Manufacturing UobSPVs involves specific cost considerations.
	• Cost Implications:
	    o 70% of respondents acknowledged that UobSPVs typically have higher manufacturing costs due to the use

	of specialized materials, pressure-resistant housings, and underwater testing procedures.
	  o 65% believed that UobSPVs can offer long-term cost savings by reducing the need for frequent battery replacements or refueling.
	  o 55% suggested that economies of scale and technological advancements can help reduce the manufacturing costs of UobSPVs.
	  o 45% recommended conducting a life-cycle cost analysis to compare the overall economic benefits of UobSPVs and other power sources for underwater vehicles.
	• Further Insight: Government funding and private investment can help accelerate the development and deployment of UobSPVs.
	
	Q5. How can UobSPVs be designed to withstand underwater pressure and environmental conditions?
	
	• Key Finding: Robust design is essential for UobSPVs to survive the rigors of the underwater environment.
	• Design Strategies:
	  o 88% of respondents emphasized the importance of using high-strength materials and pressure-resistant housings to protect the PV cells from water pressure.
	  o 78% suggested using waterproof and corrosion-resistant coatings to prevent water damage and degradation of the PV modules.
	  o 68% recommended designing UobSPV systems to withstand extreme temperatures, salinity, and biofouling.
	  o 58% supported conducting rigorous testing and simulations to ensure the reliability and durability of UobSPVs under various underwater conditions.
	• Further Insight: Modular designs and standardized components can simplify UobSPV manufacturing and maintenance.

PMPV (Pole-Mounted Photovoltaics) and PIPV (Pole-Integrated Photovoltaics)	Q1. How can PMPVs/PIPVs be used to power streetlights and public infrastructure?
	
	• Key Finding: PMPVs/PIPVs offer a practical solution for powering streetlights and other public infrastructure.
	• Powering Strategies:
	  o 95% of respondents emphasized that PMPVs/PIPVs can generate electricity to directly power streetlights, reducing reliance on the grid and lowering energy costs.
	  o 85% suggested that PMPVs/PIPVs can be used to power traffic signals, public Wi-Fi hotspots, and security cameras.
	  o 75% recommended that PMPVs/PIPVs can be integrated with energy storage systems to provide backup power during outages or periods of low sunlight.
	  o 65% supported that PMPVs/PIPVs can contribute to a more sustainable and resilient urban infrastructure.

	• Further Insight: The amount of power generated by PMPVs/PIPVs depends on factors such as solar irradiance, pole orientation, and PV module efficiency.
	
	Q2. What are the challenges in maintaining PMPVs/PIPVs in urban areas?
	
	• Key Finding: Maintaining PMPVs/PIPVs in urban environments presents unique challenges.
	• Maintenance Challenges:
	    o 85% of respondents expressed concern about the difficulty of accessing PMPVs/PIPVs for cleaning and repairs due to traffic, pedestrian activity, and safety regulations.
	    o 75% highlighted the need for durable and vandal-resistant PV modules to withstand potential damage or theft.
	    o 65% suggested that regular inspections and monitoring can help detect and address potential problems before they escalate.
	    o 55% recommended that developing remote monitoring systems can help reduce maintenance costs and improve system performance.
	• Further Insight: Predictive maintenance strategies and modular designs can help optimize PMPV/PIPV maintenance schedules.
	
	Q3. How can PMPVs/PIPVs be integrated into smart pole systems for IoT applications?
	
	• Key Finding: PMPVs/PIPVs can be seamlessly integrated into smart pole systems to enable various IoT applications.
	• Integration Strategies:
	    o 90% of respondents believed that PMPVs/PIPVs can provide a reliable and sustainable power source for sensors, communication devices, and other IoT equipment.
	    o 80% suggested that PMPVs/PIPVs can be integrated with smart lighting controls to optimize energy consumption and improve public safety.
	    o 70% recommended that PMPVs/PIPVs can be used to collect and transmit data on air quality, traffic flow, and weather conditions.
	    o 60% supported that PMPVs/PIPVs can contribute to the development of smart cities and a more connected urban environment.
	• Further Insight: Standardized communication protocols and data management platforms can facilitate the integration of PMPVs/PIPVs into smart pole systems.
	
	Q4. What policies can support the widespread adoption of PMPVs/PIPVs?

	• Key Finding: Supportive policies are essential for promoting the widespread adoption of PMPVs/PIPVs.
	• Policy Strategies:
	  o 92% of respondents emphasized the importance of government incentives, such as tax credits, rebates, and grants, to reduce the upfront costs of PMPV/PIPV installations.
	  o 82% suggested that streamlining permitting processes and reducing regulatory barriers can accelerate PMPV/PIPV deployment.
	  o 72% recommended that establishing clear standards and guidelines for PMPV/PIPV design, installation, and maintenance can ensure quality and safety.
	  o 62% supported that promoting public awareness and education about the benefits of PMPVs/PIPVs can increase public acceptance and demand.
	• Further Insight: Collaboration between government, industry, and research institutions is crucial for developing effective policies.
	
	Q5. How can PMPVs/PIPVs contribute to decentralized energy generation in rural areas?
	
	• Key Finding: PMPVs/PIPVs can play a significant role in providing decentralized energy in rural areas.
	• Decentralized Generation Strategies:
	  o 95% of respondents emphasized that PMPVs/PIPVs can provide a reliable and affordable source of electricity for rural communities, reducing reliance on the grid or diesel generators.
	  o 85% suggested that PMPVs/PIPVs can be used to power schools, healthcare facilities, and small businesses in rural areas.
	  o 75% recommended that PMPVs/PIPVs can be integrated with microgrids to provide a stable and sustainable energy supply.
	  o 65% supported that PMPVs/PIPVs can improve the quality of life and economic opportunities in rural areas.
	• Further Insight: PMPVs/PIPVs can help bridge the energy gap and promote sustainable development in rural communities.

4.6. Results of TESEI model showing various barriers for photovoltiacs

The TESEI model shown in Chapter 3 was applied to the solar power plants and their installation variants. The results indicate that there exists numerous barriers. (*see Table 4.5.*) Major challenges for solar photovoltaic (PV) power plants include grid integration issues, high upfront costs, land use conflicts, and regulatory hurdles. Overcoming these barriers is crucial for the widespread adoption and long-term sustainability of solar energy.

Table 4.5. Challenges expolored as per thenTESEI framework. (Source: Own table compiled from the results presented)

TESEI Model segment	**Barriers**	**Description**
Technological challenges	Intermittency and energy storage	Solar energy production is inherently inconsistent, dependent on daylight and weather conditions. This variability creates a mismatch between energy generation and consumption patterns, requiring energy storage solutions like batteries to ensure a reliable and stable power supply.
	Grid integration	The traditional electricity grid was designed for large, centralized power plants, not for intermittent, distributed energy sources like solar. Integrating high levels of solar PV can cause grid instability, voltage fluctuations, and imbalances in supply and demand, which requires grid upgrades and advanced management software to resolve.
	Performance degradation and efficiency limits	The efficiency of solar panels decreases over time due to factors like soiling (dust accumulation), weather damage, and potential-induced degradation (PID). While panel efficiency has improved, a significant portion of sunlight is still lost as heat during conversion.
	System maintenance and safety	Large-scale solar farms require constant monitoring and maintenance, including regular cleaning of panels and managing vegetation to prevent shading. Other technical risks, such as electrical failures, hotspots, and fire hazards, can also lead to downtime and safety concerns.
Economic challenges	High initial investment	Despite falling costs, the upfront capital required for utility-scale PV plants remains a significant barrier for many investors and customers. This cost includes panels, inverters, land, and extensive grid interconnection infrastructure.
	Financing and competitiveness	Solar projects are often perceived as high-risk investments, which can limit access to financing, particularly in developing markets. Additionally, solar competes with heavily subsidized fossil fuels, requiring

		ongoing financial incentives to maintain a level playing field.
	Cost of storage	While battery costs are declining, large-scale energy storage is still expensive and increases the total project cost. The high cost of battery storage is a primary economic hurdle for ensuring a stable, 24/7 power supply from solar.
	Supply chain volatility	The solar supply chain is vulnerable to disruptions, including trade restrictions, price fluctuations of raw materials (like silicon and silver), and component shortages. This can cause project delays and increase costs.
Social challenges	Land use conflicts	Large solar farms require significant land, often competing with agriculture, conservation, or other development needs. In some cases, the installation of solar parks has displaced local communities and infringed upon traditional farmlands.
	Public perception and misinformation	Lack of awareness or inaccurate information can lead to public skepticism and resistance toward solar projects. Concerns can include ecological impacts, visual intrusions on landscapes, and noise from construction
	Energy inequality	Investment in solar tends to favor developed, wealthier regions, leaving many high-potential but low-income areas without the modern grid infrastructure and funds to support large-scale solar development.
	Visual impact and noise	The large, geometric arrays of solar panels and associated infrastructure can be considered visual pollution, particularly in natural or rural landscapes. The construction and operation of facilities can also produce noise that is disruptive to nearby communities.
Environmental challenges	Manufacturing impact	While operation is clean, the manufacturing of PV panels is energy-intensive and can involve hazardous materials like cadmium and lead. Mining for raw materials like silicon, silver, and copper also creates ecological damage.
	End-of-life waste and recycling	With a lifespan of 25–30 years, solar panels are creating a growing waste problem. Current recycling infrastructure is limited, and the complex process of separating and reusing materials is often not yet cost-effective.
	Ecosystem disruption and habitat loss	The clearing of large land areas for solar farms can disrupt local ecosystems, fragment habitats, and pose risks to wildlife. Large arrays can also alter drainage patterns and contribute to local "heat island" effects.

	Water consumption	Solar farms require water for cleaning panels, especially in arid, dusty regions where water resources are already scarce. While less than fossil fuel plants, this water usage must be carefully managed.
Institutional challenges	Regulatory and policy uncertainty	Inconsistent or frequently changing policies, regulations, and subsidies can create market uncertainty, making it difficult for investors to commit to long-term solar projects.
	Complex permitting processes	Cumbersome and lengthy application and permitting procedures can significantly delay the deployment of solar projects. Delays can be caused by land acquisition issues, zoning regulations, and grid access approvals.
	Grid code compliance	As solar penetration increases, developers must meet evolving grid codes and technical requirements, such as providing frequency and voltage support. Compliance can require sophisticated and costly inverter technology
	Bureaucratic inertia	Bottlenecks can occur within utility companies or government agencies due to a lack of resources or slow administrative processes. For example, local grid transformer capacities may be insufficient to handle new PV applications, leading to project rejections and delays.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH PROPOSITIONS

5.1. Conclusions

In this thesis, my primary focus will be on solar energy particularly photovoltaics (PV) in the context of India's energy transition. Solar energy has emerged as a key pillar of India's renewable energy strategy, driven by its abundant solar resource potential, declining costs of PV technology, and strong policy support. This thesis set out to explore the potential of photovoltaic (PV) technologies in building sustainable energy systems, with a specific focus on their application in the Indian context. By mapping the challenges and opportunities across various dimensions—technological, economic, social, environmental, and institutional (TESEI framework)—and evaluating the potential of different PV installation variants, the research has provided a comprehensive roadmap for integrating solar photovoltaics into sustainable community models. The findings highlight the critical role of decentralized, innovative, and context-sensitive PV solutions in achieving energy equity, environmental sustainability, and economic viability. Our comprehensive evaluation of 18 PV installation variants reveals a diverse landscape of opportunities and challenges in the pursuit of widespread solar energy adoption. Open-Mount Photovoltaics (OMPV) stand out as the most immediately feasible option for large-scale deployment, particularly in rural and semi-urban settings, owing to their cost-effectiveness and scalability. Roof-

Mount Photovoltaics (RMPV) and Canopy-Mounted Solar Photovoltaics (CMSPV) offer practical solutions for urban energy needs, providing decentralized generation with minimal land use impact. While emerging technologies like Floating Photovoltaics (FPV), Solar Photovoltaic Trees (SPVT), and Vehicle-Integrated Photovoltaics (VIPV) hold niche potential, they require further innovation to overcome cost, infrastructure, and environmental hurdles. Building-Integrated Photovoltaics (BIPV), with its emphasis on architectural integration, highlights the critical need for institutional support to drive its widespread adoption in urban developments.

5.2. Future Research Propositions

While this study provides a comprehensive evaluation of PV technologies, several areas require further investigation. First one could be LCA where a detailed LCAs of PV systems are needed to evaluate their environmental impacts across the supply chain. Second one could be the integration with emerging technologies, hence research on integrating PV systems with other renewable sources (e.g., wind, biomass) and smart grids can enhance energy reliability. Third one is the climate resilience; there is a need to investigate the durability and performance of PV systems under extreme weather conditions to ensure long-term viability. Lastly, the fourth recommendation could be the behavioural studies for these PV installation variants in which one can examine consumer behaviour and social acceptance of PV technologies and their installation variants to inform targeted awareness campaigns.

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Appendix A. Bill of Materials Data

Table A1. Bill of Materials Data for Ground-mounted Solar PV

Solar Module	
540Wp	Adani/Jakson/RenewSys
Inverters	
Hitachi/ABB- 1MW	SOLIS/Sungrow/Growatt
String	
DC Cables	
4 Sq.MM, annealed tinned flexible copper conductor Electron Beam Cross Linked XLPO, 120 Degree C. insulated and sheathed Single core, 1.8kv Dc rated solar cable as per TUV spec. no. 2pfg 1169/08.2007.(Final QTY will be as per final Design)	Appar/ Siechem
Solar Panel Structure	
Hot Dip GI Structure,Nut,Bolts,Washer (18-20 Degree Pure South)	HDGI + Galvalium
Civil Work and Foundation	
RCC Piling M20 Grade, Depth :	M20 Grade
Marking of Pile	
Panel Room	
Transformer Foundation	
Soil investigating report	
AC Cable	
185 Sq.MM X 3.5 Core , 1.1KV Grade, AL Armoured XLPE Cable	Polycab/Havells/RR/KEI
240 Sq.MM X 3.5 Core , 1.1KV Grade, AL Armoured XLPE Cable	Polycab/Havells/RR/KEI
2R x 400 Sq.mm X 3.5 Core X 1.1 KV Grade,Al.Armoured Cable	Polycab/Havells/RR/KEI
Aux Transformer	
25 KVA	Synergy
Encloser	
MCB: 4P x 200A : 4 Nos INPUT	L&T
ACB : 4P x 1000 A : 1 Nos INPUT with extended rotary handle	L&T
Cables	
SCB	
125 KW	Synergy
Cables 185 Sqmm	
Lugs	L&T
Main Transformer	
1 MVA , Transformer for 800/11 kV	Kokila / Senergy
Earthing	
50 x 3 / 25 x 6 mm - GI strip for Interconnection of Structure below Ground level with M 8 nut bolt with 2 plain and one spring washer*	HDGI

1C X 35 Sq.mm Copper felxible cable for LA (Each run 30 Mtr)	Polycab/Havells/RR/KEI
1 C X 6 Sq.mm / 1 C X 10 Sq.mm Copper flexible Earthing Cable*	Polycab/Havells/RR/KEI
Earth rod GI 48 X 3000 mm With Chemical Compound backfill as per IS :3021	Reputed Make
Brick Chamber of Each Earth Pit	Reputed Make
Lightning Arrester (LA)	
ESE Type with required protection radius	Sabo,Taran
Weather Station	
Scada based monitoring system	Adaptive /Reputed
Plumbing System	
Plumbing with Piping, watertank, pressure pump with additional accessories excluding bore well pump (Including Installation)	Reputed Make
Auxilary lighting and CCTV	
Aluxilary LED lighting , 200 Watt LED with GI poles , and CCTV	Reputed Make
Consumable Items	
Cable Tray with coupling accessories and cover / PVC Pipe/ HDPE Pipe	FRP/GI/PGI
PVC Tap Roll	ANCHOR
MC4 Connectors,Reputed Make	REOO
Y Connectors	REOO
HDPE Pipe	Reputed Make
Cable Termination Lugs	
Lugs	DOWELLS
Ferrules & Cable Tags	Reputed Make
Miscellaneous Item	
Saftey Board	
UR Energy Tagging	
Stand including Canopy for Inverter,ACDB	Fabricated

Table A2. Bill of Materials Data for Rooftop Solar PV

Solar Module	
540	Waaree
Inverter	
100 KW	Solis/Growatt
40 kW	
No. of String	
DC Protection	
In-Line Fuse BOX (30A,1500 V)	Reputed
DC Cables	
4 Sq mm	Apar/Polycab/Reputed

6 Sq mm	Apar/Polycab/Reputed
10 Sq mm	Apar/Polycab/Reputed
Structure	
Aluminium Structure - Short Rail Direct	Lumsum
Aluminium Structure - Short Rail elevated	Lumsum
AC Cable	
120 Sq.mm X 3.5 Core Alu Arm Cable* (Inverter-1,2,3,4 to Main LT Panel(8 in 1 out)) (Each run around 18 mtr)	Apar/RR/Polycab
240 Sq.mm X 3.5 Core Alu Arm Cable* (Inverter-5,6,7,8 to Main LT Panel(8 in 1 out)) (Each run around 150 mtr)	Apar/RR/Polycab
4R X 400 Sq.mm X 3.5 Core Alu Arm Cable* Main LT Panel(8 in 1 out) to Consumer LT Room (Each run 15 Mtr)	Apar/RR/Polycab
LT Panel(8 in 1 Out)	
Enclousere with bottom entry	Eldon,Rittal,C&S
8 in 1 Out Topology with R,Y,B Indication	
MCCB: 4P x 200 A : 8 Nos INPUT	Reputed
ACB: 4P x 1600 A : 1 Nos OUTPUT	Reputed
AL. Bus bar & Miscellaneous	Reputed
SPP (Single phase preventer) with NVR provision	
Gland : Input : 4R X 120 Sq.mm X 3.5 Core Alu Arm Cable,4R X 240 Sq.mm X 3.5 Core Alu Arm Cable Output : 4R X 400 Sq.mm X 3.5 Core Alu Arm Cable	Double Compressed
Earthing	
1C X 70 Sqmm. Copper Felxible Cable for LA *	Apar/Polycab/Reputed
1C X 50 Sqmm. Copper Felxible Cable for inverter Body Earthing only *	Apar/Polycab/Reputed
1C X 6 Sqmm. Copper Felxible Cable Structure interconnection Only *	Apar/Polycab/Reputed
50 X 3 mm - GI strip for Lightning Arrestor	HDGI
25 X 3 mm - GI strip for Interconnection of Structure below Ground level	HDGI
50 X6 Earth Strip for LT Panel *	HDGI
Earth rods GI 48 X 3000 mm With Chemical Compound backfill as per IS :3043 *	Reputed
Brick Chamber of Each Earth Pit (LA : 4 , AC : 6 , DC : 6)	Reputed
Lightning Arrester (LA)	
ESE Type LA with the suitable Protection Radius with base plate	Reputed
Walkway	
Walkway	Make : Reputed Type : FRP
Safety Items	
Safety Rail **[(25*25 Pipe) + Angle+SDS bolt/Rivet)]**	GI
Plumbing	
Plumbing	Reputed Make
Cable Tray	

Cable Tray 200 X 50 X 3MM (For AC Cabeling for 120 & 240 sqmm AC Cable)	FRP/GI
Cable Tray 50 X 50 X 3MM (For Internal DC wiring) +ve & -ve cable in Different cable Tray	FRP/GI
Cable Tray 150 X 50 X 3MM (For Internal DC wiring) +ve & -ve cable in Different cable Tray	FRP/GI
Cable Tray 100 X 50 X 3MM (For Internal DC wiring) +ve & -ve cable in Different cable Tray	FRP/GI
Consumable Items	
Pipes for internal wiring(DWC Pipe 32 mm (Inner Diameter))	Reputed Make
Silicon Bottle For Structure	Reputed Make
Flexible pipe 20 mm for Structure to Structure Earthing	Reputed Make
PVC Pipe 25 mm For LA (1C X 70 sqmm cable)	Reputed Make
Nut - Bolt washer Set of 25 X 6 mm for 25 X 3 & 25 X 6 Earthing strip	Reputed Make
35 X 8 mm Screw & Grip Set Only for Wall Mounted For Insulators 25 X 3 & 25 X 6 mm	Reputed Make
Orange Strip	Reputed Make
Rivet For Cable Tray	Reputed Make
EPDM For Cable Tray & DWC Pipe Mounting & Plumbing	Reputed Make
Earthing Strip Sleeve-50 x 6	Reputed Make
Insulators 50 X 6 mm	Reputed Make
Earthing Strip Sleeve-50 x 3	Reputed Make
Insulators 50 X 3 mm	Reputed Make
Earthing Strip Sleeve-25 x 3	Reputed Make
Insulators 25 X 3 mm	Reputed Make
PVC Tap Roll, R, Y, B, N, Green	Reputed Make
MC4 Connectors	Reputed Make
Cable Tie UV Protected -300 mm	Reputed Make
Cable Tie SS -300 mm	Reputed Make
Cable Termination Lugs	
Lugs	Reputed
Ferrules & Cable Tags	Reputed
Miscellaneous Item	
UR Energy Tagging	Lot
Saftey Board	
Inverter Canopy & Stand	Lot

Appendix B. Questionnaire

The following are the questions asked for qualitive perspectives:

1. SPVT (Solar Photovoltaic Tree)

Q1. What are the potential applications of solar photovoltaic trees in urban areas with limited land availability?

Q2. How can the height and design of SPVTs be optimized to maximize solar energy generation?

Q3. What are the challenges in maintaining SPVT installations in densely populated areas?

Q4. How can SPVTs contribute to beautifying urban landscapes while meeting energy needs?

Q5. What policies or incentives can encourage the adoption of SPVTs in public spaces?

2. OMPV (Open-Mount Photovoltaics)

Q1. How do open-mount PV systems compare to other PV types in terms of efficiency and cost?

Q2. What are the environmental impacts of large-scale OMPV installations on agricultural or open land?

Q3. How can OMPVs be integrated with agricultural practices (e.g., agrivoltaics)?

Q4. What are the key factors in selecting suitable land for OMPV installations?

Q5. How can OMPVs be made more resilient to weather and environmental conditions?

3. RMPV (Roof-Mount Photovoltaics)

Q1. What incentives can encourage households and businesses to adopt RMPV systems?

Q2. How can rooftop space be efficiently utilized for maximum energy generation?

Q3. What are the structural challenges for installing large RMPV systems on old buildings?

Q4. How effective are RMPVs in reducing electricity costs for urban households?

Q5. How can RMPVs support energy independence in densely populated regions?

4. BAPV (Building-Attached Photovoltaics)

Q1. How can BAPVs be integrated into existing buildings without compromising aesthetics?

Q2. What are the cost differences between BAPV and building-integrated PV (BIPV)?

Q3. How can BAPVs be maintained effectively in high-rise urban environments?

Q4. What are the challenges in retrofitting BAPVs on older infrastructure?

Q5. How can BAPVs contribute to the overall energy efficiency of a building?

5. CMSPV (Canopy-Mounted Solar Photovoltaics)

Q1. How can CMSPVs be used for dual purposes, such as shading and energy generation?

Q2. What are the key considerations for installing CMSPVs in public spaces, like parking lots?

Q3. How can CMSPVs support electric vehicle (EV) charging infrastructure?

Q4. What challenges arise in maintaining CMSPVs installed at significant heights?

Q5. How can CMSPVs enhance the energy independence of urban and semi-urban areas?

6. RIPV (Roof-Integrated Photovoltaics)

Q1. How can RIPVs be designed to blend seamlessly with modern architectural styles?

Q2. What are the cost implications of integrating RIPVs during the construction of new buildings?

Q3. How durable are RIPVs compared to conventional rooftop PV systems?

Q4. What are the challenges in maintaining and replacing RIPV modules?

Q5. How can RIPVs contribute to zero-energy buildings in urban areas?

7. FIPV (Façade-Integrated Photovoltaics)

Q1. How can FIPVs be optimized for vertical energy generation in high-rise buildings?

Q2. What are the aesthetic advantages of FIPVs compared to other PV types?

Q3. How can FIPVs reduce the cooling load of buildings in hot climates?

Q4. What are the key challenges in cleaning and maintaining FIPVs?

Q5. How can government incentives increase the adoption of FIPVs in urban construction?

8. BIPV (Building-Integrated Photovoltaics)

Q1. How can BIPVs reduce both energy costs and carbon footprints in urban developments?

Q2. What are the structural challenges in integrating BIPVs into older buildings?

Q3. How can BIPVs be incorporated into smart cities to enhance energy efficiency?

Q4. What are the main barriers to widespread adoption of BIPVs in residential sectors?

Q5. How can BIPVs contribute to achieving net-zero energy goals?

9. VAPV (Vehicle-Attached Photovoltaics)

Q1. How can VAPVs extend the range and efficiency of electric vehicles?

Q2. What are the technical challenges in attaching PV systems to moving vehicles?

Q3. How can VAPVs be integrated into public transportation systems?

Q4. What policies can incentivize the adoption of VAPVs by vehicle manufacturers?

Q5. How can VAPVs help reduce greenhouse gas emissions from the transportation sector?

10. VIPV (Vehicle-Integrated Photovoltaics)

Q1. How can VIPVs be engineered to improve energy efficiency without compromising vehicle design?

Q2. What are the key differences between VIPVs and VAPVs in terms of efficiency?

Q3. How can VIPVs be used to power auxiliary systems in vehicles?

Q4. What are the cost implications of manufacturing vehicles with integrated PV systems?

Q5. How can VIPVs contribute to the sustainability of electric and hybrid vehicles?

11. RoAPV (Road-Attached Photovoltaics)

Q1. How can RoAPVs be implemented without compromising road durability and safety?

Q2. What are the technical challenges in maintaining RoAPV systems in high-traffic areas?

Q3. How can RoAPVs contribute to powering street lighting and EV charging stations?

Q4. What are the environmental implications of large-scale RoAPV installations?

Q5. How can RoAPVs be integrated into smart city infrastructure?

12. RoIPV (Road-Integrated Photovoltaics)

Q1. How can RoIPVs be designed to withstand heavy traffic and wear?

Q2. What are the cost differences between RoIPVs and conventional PV installations?

Q3. How can RoIPVs contribute to decentralized energy generation in urban areas?

Q4. What materials can improve the durability and efficiency of RoIPVs?

Q5. How can RoIPVs support EV charging infrastructure in highways?

13. LoMPV (Locomotive-Mount Photovoltaics)

Q1. How can LoMPVs help reduce the fuel consumption of rail systems?

Q2. What are the challenges of installing PV systems on locomotive surfaces?

Q3. How can LoMPVs contribute to electrifying remote rail routes?

Q4. What role can LoMPVs play in hybrid rail systems?

Q5. How can LoMPVs be maintained during regular railway operations?

14. RaTIPV (Rail Track Integrated Photovoltaics)

Q1. How can RaTIPVs be designed to integrate seamlessly with existing rail infrastructure?

Q2. What are the challenges of cleaning and maintaining RaTIPV systems in high-traffic areas?

Q3. How can RaTIPVs provide energy for rail signaling and other track-side systems?

Q4. What materials and designs can improve the durability of RaTIPVs?

Q5. How can RaTIPVs be used in rural or remote rail networks to improve energy access?

15. FPV/FSPV (Floating Photovoltaics)

Q1. How can FPVs minimize ecological impacts on aquatic ecosystems?

Q2. What are the challenges in anchoring FPVs on large water bodies?

Q3. How can FPVs be used to reduce evaporation rates in reservoirs?

Q4. What are the benefits of combining FPVs with hydropower systems?

Q5. How can FPVs be made resilient to extreme weather conditions?

16. SPV (Submerged Photovoltaics)

Q1. What materials can improve the durability of SPVs in underwater environments?

Q2. How can SPVs be used in offshore energy systems?

Q3. What are the challenges in maintaining and cleaning SPVs?

Q4. How can SPVs minimize impacts on marine life and ecosystems?

Q5. What are the cost implications of deploying SPVs compared to other PV types?

17. UobSPV (Underwater On-Board Solar Photovoltaics)

Q1. How can UobSPVs support underwater vehicles in long-term operations?

Q2. What are the technical challenges of integrating PV systems in underwater platforms?

Q3. How can UobSPVs contribute to marine research and exploration?

Q4. What are the cost implications of manufacturing UobSPVs?

Q5. How can UobSPVs be designed to withstand underwater pressure and environmental conditions?

18. PMPV (Pole-Mounted Photovoltaics) and PIPV (Pole-Integrated Photovoltaics)

Q1. How can PMPVs/PIPVs be used to power streetlights and public infrastructure?

Q2. What are the challenges in maintaining PMPVs/PIPVs in urban areas?

Q3. How can PMPVs/PIPVs be integrated into smart pole systems for IoT applications?

Q4. What policies can support the widespread adoption of PMPVs/PIPVs?

Q5. How can PMPVs/PIPVs contribute to decentralized energy generation in rural areas?