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Economic Potential of Solar Projects in India: Assessing Levelized Cost of Electricity andPayback Period withVariations in PV Module Efficiency and Solar Irradiation

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Research Question

How do variations in solar irradiation and PV module efficiency impact the overall feasibility and cost-effectiveness of solar projects in India?

Abstract

India is endowed with vast solar resources, with about 5,000 trillion kWh per year of energy incident over India's land area, with most parts receiving 4-7 kWh per sqm per day. The National Institute of Solar Energy (NISE) has assessed the country's solar potential to be about 748 GW. The government is bullish on realizing this solar potential, setting out ambitious targets to install 500 GW of non-fossil fuel capacity by 2030, with Solar projects contributing a major chunk of it. Reports suggest that investments up to $294bn would be required to meet India's solar and wind targets. However, this capital expenditure can be reduced or controlled by deploying our solar projects prudentially. This paper intends to quantify the effect of variations in Solar PV module efficiency due to varying technology and changes in solar irradiation according to differing geographies on the cost-effectiveness of Solar projects through the calculation of the Payback period and Levelized Cost of Electricity for Solar PV projects in different parts of India. Comparison of these techno-economic factors will aid policymakers and project developers in decision-making and deploying their resources to achieve maximum financial output. The results reveal that higher module efficiency and greater solar irradiation significantly bring down the cost of Solar projects, bringing it even below the global average LCOE of solar PV of 49$/MWh for higher efficiencies and reducing the payback period to as low as shorter than 5 years. Therefore, this paper aims to provide valuable insights to the policymakers and investors working in the solar energy sector in India to help build a clean, secure, and resilient energy future for India.

I. Introduction

India's population and economy are growing at an unprecedented rate, becoming the world's largest population and the fifth-largest economy. This surge in population and economy is coupled with significant development in the urbanization and manufacturing sectors of India, leading to the rapid increase in India's energy demands. Energy consumption in India has more than doubled since 2000, and near-universal household access to electricity was achieved in 2019, meaning that over 900 million citizens have gained an electrical connection in less than two decades (IEA 2021 India Outlook). This growing demand has been predominantly met through fossil fuels, including coal, oil, and natural gas—all three contributing to more than 75% of India's energy mix—a large fraction of which is imported (34%) (IEA 2021 India Energy Mix). However, increasing resource scarcity and intense geopolitical tensions have led to a significant increase in fuel prices in India, reaching an all-time high in the nation, and putting immense pressure on the energy sector and its policymakers. Furthermore, the consumption of these fossil fuels is responsible for the majority of climate change-causing greenhouse gas emissions, which exacerbate the impacts of global warming. India's CO_2 emissions from fuel combustion have been on an upward trajectory, increasing by 156% since 2000, becoming the 3rd largest in the world (IEA 2021 India Emissions). This is a step backwards from India's carbon neutrality targets, which aim to reach net zero by 2070, set by the government in COP26 (Ministry of External Affairs 2021). This confluence of rising fuel prices and environmental degradation has urged India to rethink its energy strategy and pivot towards more sustainable alternatives. Avoiding the use of coal to serve as the bedrock of its imminent development, Prime Minister Narendra Modi has announced ambitious targets for 2030, including installing 500 gigawatts of renewable energy capacity, reducing the emissions intensity of its economy by 45%, and reducing a billion tons of CO_2 (IEA 2022). To realize these targets, Solar Photovoltaic remains, by far, one of the most potent pathways.

India is endowed with vast solar energy potential. About 5,000 trillion kWh per year of energy is incident over India's land area, with most parts receiving 74–7 kWh per sq m per day, multiple times over the country's daily energy requirements (MNRE 2024). Solar photovoltaic power can effectively be harnessed to utilize this abundant resource to provide huge energy scalability in India. Solar PV provides the ability to generate electricity on a distributed basis and enables rapid capacity addition with short lead times. Off-grid decentralized and low-temperature applications of Solar PV are beneficial for the rural household, and meeting other energy needs for power, heating, and cooling comes as an aid in both rural and urban areas. From an energy security perspective, solar is the most secure of all sources since it is abundantly available (MNRE 2024). Theoretically, a small fraction of the total incident solar energy can meet the entire country's power requirements, only if captured effectively. However, solar energy still represents only 4.6% of India's installed power capacity (IEA 2021 Electricity). But this is fast changing.

The Government of India has launched key initiatives like the National Solar Mission (NSM) with active participation from States to promote ecologically sustainable growth while addressing India's energy security challenges. The Mission's objective is to establish India as a global leader in solar energy by creating the policy conditions for solar technology diffusion across the country as quickly as possible. This is in line with India's Nationally Determined Contributions (NDCs) target to achieve about 50 per cent cumulative electric power installed capacity from non-fossil fuel-based energy resources and to reduce the emission intensity of its GDP by 45 percent from the 2005 level by 2030. (MNRE 2024). These efforts have brought India to the 5th position in the Global Solar Capacity rankings and 4th for total renewable capacity additions. The installed solar energy capacity of India has increased by 30 times in the last 9 years and stands at 85.47 GW as of Jun 2024. (Invest India 2024).

However, the imminent challenge that lies ahead is the need for massive investments in the renewable sector to realize this phenomenal potential of the country. Reports suggest that India's financing capacity must increase nearly threefold on average by 2030 from an investment capacity of approximately $75 billion in the previous eight years to achieve its heightened ambitions of tripling its renewable energy capacity (Neshwin Rodrigues et. Al 2023).

Given these economic struggles, what remains imperative is that India needs to deploy its solar resources judiciously to achieve maximum efficiency and the highest economic gains. This would require a careful analysis of the geographies where these Solar PV projects are installed, taking into account the solar irradiance, direct and diffused, reaching different parts of the country. In addition, in-depth knowledge of Solar PV module technologies would help us understand their varying efficiencies, workings, upsides, and drawbacks. A combination of both would allow policymakers to make informed decisions regarding solar PV instalments. In this way, selecting the appropriate geographic locations for Solar PV projects concerning the solar irradiance received by them and the particular Solar PV module technology could potentially help reduce the massive capex required for India's illustrious solar targets. This selection process would be governed by analyzing the economic output of PV installations in different regions of the country while considering factors like high upfront costs for Solar PV panels, variations in solar irradiations due to weather and geographical factors, and scarcity of materials involved in the production of advanced Solar PV panels.

Existing studies provide us with detailed, precise information about solar irradiation levels in regions of India and use existing technologies to estimate total solar output possible in different geographies. In contrast, this study focuses on calculating techno-economic metrics of Solar PV, essential in understanding the long-term feasibility of the installation of PV systems in regions with strict financial constraints. Moreover, with increasingly more efficient PV technologies finding their way to the commercial picture, it is crucial to take into account the varying efficiencies of these emerging solar cells while calculating the cost-effectiveness of these technologies. This would allow regions to have a comprehensive understanding of the economic benefit they would reap from the installation of different solar PV technologies based on their specific solar irradiation levels, allowing them to make strategic decisions to improve the cost-effectiveness of their regional energy supply and aid to the country's decarbonization goals. This paper, therefore, employs judicious methods to calculate techno-economic metrics like Levelized Cost of Energy and Pay-back periods of Solar PV projects in different parts of India, taking into account the variations in solar irradiance due to varying geographies of these regions and for different Solar PV module efficiencies. Its novel results will allow policymakers and project developers to choose the appropriate region and Solar PV module for the development of their projects to maximize the project's cost-effectiveness and aid the nation's long-term energy transformation process.

II. Literature Review

Solar energy is the most abundant permanent energy resource on earth, and it is available for use in its direct (solar radiation) and indirect (wind, biomass, hydro, ocean, etc.) forms. Even if only 0.1% of the Sun's energy that reaches the Earth's surface could be converted at an efficiency of only 10%, it would be four times the world's total generating capacity of about 3,000 GW. We could also say that the total annual solar radiation falling on the earth is more than 7,500 times the world's total annual primary energy consumption of 450 EJ.

Therefore, it is easy to conclude that solar energy is the most abundant energy source available to us, and if its power is harnessed appropriately, it bears the ability to eradicate all dearth of energy resources.

India is the third-largest consumer of energy in the world, and with a population of approximately 1.4 billion and the world's fastest-major growing economy, India's energy demand is growing rapidly (ITA 2024). Fossil fuels dominate India's power sector, but the country has ambitious goals to significantly increase the share of renewable energy. Significant efforts are being made to reduce the growth of greenhouse gas emissions and dependence on energy imports, while at the same time enhancing India's energy security. Given the pressing need for India to pivot to non-fossil fuel sources and renewables to fight the increasing energy security risks for the world's third largest energy importer due to tight markets and contribute to the global net zero emissions goal, Prime Minister Narendra Modi announced in COP26 five ambitious targets for India: reaching 500 GW non-fossil energy capacity by 2030; fulfilling 50% of its energy requirements through renewable energy by 2030; reducing total projected carbon emissions by one billion tons from now to 2030; reducing the carbon intensity of the economy by 45% by 2030 over 2005 levels; achieving the target of net zero emissions by 2070. Realizing the competence of Solar energy, it remains at the forefront of the significant strides being taken by India to achieve these illustrious targets (ITA 2024).

Solar power is set to represent more than 50% of the renewable energy mix by 2030, and this is becoming possible due to both technological advancements and swift policy changes by the government and energy sector of India (ITA 2024). Key initiatives by the government include: permitting Foreign Direct Investment (FDI) up to 100 percent under the automatic route; Declaration of trajectory for Renewable Purchase Obligation (RPO) up to the year 2029-30; and the Grid Connected Solar Rooftop Programme that aims to achieve a cumulative installed capacity of 40,000 MW from Grid Connected Rooftop Solar (RTS) projects, among many other (MNRE 2024). These initiatives came into the picture due to the incredible breakthroughs in Solar Power technologies, especially Solar Photovoltaic (Solar PV) which have transformed the way we harness the sun's energy.

Solar Photovoltaics convert sunlight directly into electricity. When light shines on a photovoltaic (PV) cell—also called a solar cell—that light may be reflected, absorbed, or pass right through the cell. The PV cell is composed of semiconductor material. When the semiconductor is exposed to light, it absorbs the light's energy and transfers it to negatively charged particles in the material called electrons. This extra energy allows the electrons to flow through the material as an electrical current. This current is extracted through conductive metal contacts—the grid-like lines on a solar cell—and can then be used to power homes and the rest of the electric grid (Energy.gov/Energy Efficiency and Renewable Energy). This means that Solar Photovoltaics require no heat engine to generate electricity from Sun's energy, in contrast to other Solar technologies like CSP or Solar Thermal Power. This allows Solar Photovoltaics to be much more rugged, simple in design, and involve much less movement, resulting in very little maintenance. The biggest advantage of solar photovoltaic devices is, perhaps, that they can be constructed as stand-alone systems to give outputs from microwatts to megawatts. This allows Solar PV to find a wide array of applications—from street lighting systems, water pumping systems, community TV systems, and integrated rural electricity supply systems to communications, satellites, space vehicles, and even multi-megawatt-scale power plants—essential applications for the development of both rural and urban parts of India. However, it is crucial to take into account factors that affect the amount of electricity generated by these Solar PV systems given their cost to understand the economics and cost-effectiveness of these projects, guiding policymakers and project developers in the appropriate direction to achieve maximum utility out of these projects. In this paper, we will enumerate the major two factors affecting the economic feasibility of these Solar PV projects—solar panel efficiency and Solar Irradiation—and later go on to calculate techno-economic metrics based on these factors to compare the economic output of these Solar panels in different regions of India.

The conversion efficiency of a photovoltaic (PV) cell, or solar cell, is the percentage of the solar energy shining on a PV device that is converted into usable electricity. Improving this conversion efficiency is a key goal of research and helps make PV technologies cost-competitive with conventional sources of energy (Department of Energy). In the early days of solar cells in the 1960s and 1970s, more energy was required to produce a cell than it could ever deliver during its lifetime. Since then, dramatic improvements have taken place in their efficiency and manufacturing methods, significantly improving cell efficiency and panel lifetime.
Technological strides over the years have led to the development of an array of Solar PV technologies characterized by different types of solar cells and efficiencies. Some of the most common Solar PV technologies used in India today are:

- M*onocrystalline solar panels*
- Polycrystalline solar panels
- Thin-film solar panels
- *Amorphous silicon panels*

Solar panel efficiency of these technologies is determined by two main factors: the photovoltaic (PV) cell efficiency, based on the solar cell design and silicon type, and the total panel efficiency, based on the cell layout, configuration, and panel size. The efficiencies of these panels vary, owing mainly to the different types of solar cells used in each panel. We will elaborate more on Solar cell efficiencies when we collect data for our methodology later. However, in addition to efficiency, the cost-effectiveness of these projects also greatly depends on the location where these panels are installed to calculate the total output of these systems. This is due to differences in solar irradiance from one region to another.

Solar radiation, often called the solar resource or just sunlight, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resources. Every location on Earth receives sunlight for at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:Geographic location,Time of day,Season,Local landscape,Local weather(Department of Energy/ Solar Radiation Basics). India has a very varied topography with ranges of landscapes that include mountains, plains, forests, plateaus, deserts, and also coastal plains. Various climatic conditions are experienced in India due to its various physical features, which also impact the direct and diffused sunlight received by these regions. This results in some regions like Arunachal Pradesh receiving as little as 894 kWh/m2 of direct solar irradiance per year to as high as 1764 kWh/m2 in Rajasthan (Global Solar Atlas 2024). Nevertheless, most parts of India have 300-330 sunny days in a year, which is equivalent to over 5000 trillion kWh per year more than India's total energy consumption per year, and average solar incidence stands at a robust 4-7 kWh/sq. meter/day, providing India with exceptional Solar potential (EEREM 2024).

In my study, the following literature came of great use:

V Spatial mapping of renewable energy potential by T.V. Ramachandra, B.V. Shruthi (Ramachandra et. al)

o While laying down methods to calculate the renewable energy potential of a region, it presents ways to calculate global solar irradiation data for regions where stations for measurements are unavailable through various probable relationships among the parameters such as (i) sunshine and cloudiness and (ii) extra-terrestrial radiation allowing for its depletion by absorption and scattering in the atmosphere. Such data helps in identifying the potential sites for harnessing solar energy.

V Analysis of the Key Factors affecting Levelized Cost of electricity of Solar PV in India by Nisarg Shah (Nisarg 2018)

o Given the targets set by the Indian government for the deployment of 100 GW of Solar PV by the year 2022, which accounts for around $100 billion in investment, it is important to rationalize power tariffs by analyzing the impact of various sets of factors affecting the LCOE, which the present paper does This analysis will be helpful to investors for avoiding the problem of underbidding and/or overbidding. This analysis is also helpful to policymakers in maintaining the competitive nature of markets as well as the sustainability of the market.

V Quantifying renewable energy potential and realized capacity in India: Opportunities and challenges by Kieran M. R. Hunt, Hannah C. Bloomfield (Kieran et. Al 2023)

o Using gridded estimates of existing installed capacity combined with their historical capacity factor dataset, the study creates a simple but effective renewable production model to identify weaknesses in the existing grid and discuss potential avenues for future renewable investment. This benefits the policymakers and project developers to make informed and analytical decisions.

III. Methodology

To assess how Solar PV efficiencies and Solar irradiation affect the economic feasibility of solar projects in India, we will follow a method that will involve the following steps:

Collecting reliable data for Solar Irradiation incidents in different regions of India.

Gathering data related to the varying Solar PV module efficiencies used most commonly in India.

Utilizing the gathered data to calculate techno-economic metrics - Payback Period and Levelized Cost of Electricity - of Solar project installations in different parts of India.

i. Solar Irradiation Data:

The solar irradiation data is collected for 28 states and 8 union territories of India from The World Bank Group and Energy Sector Management Assistance Program-funded initiative Global Solar Atlas, providing accurate and reliable global solar data through GIS layers and poster maps.

The following data have been collected for each region annually:

Direct normal irradiation (DNI) (in kWh/m2): It is the amount of solar radiation intercepted per unit area of a surface, which is held at right angles to the rays that propagate in a straight line from the sun at its instantaneous position in the sky (Amos Madhlopa 2022)

Global horizontal irradiation (GHI) (in kWh/m2): Global Horizontal Irradiance (GHI) is the amount of terrestrial irradiance falling on a surface horizontal to the surface of the earth (SNL 2024)

Diffuse Horizontal Irradiation (DIF) (in kWh/m2): Diffuse horizontal irradiance (DHI) is the terrestrial irradiance received by a horizontal surface that has been scattered or diffused by the atmosphere. (SNL 2024)
The data has been collected state-wise to allow decision-making on solar project development by the respective state governments after analyzing their economic profits from these solar projects, without any scope of interstate dispute.
The data is represented in the following Table 1.

STATES	Direct normal irradiation (DNI) (per year) (kWh/m2)	Global horizontalirradiation (GHI) (per year) (kWh/m2)	Diffuse horizontal irradiation (DIF) (kWh/m2)
Andhra Pradesh (15.924091°, 080.186381°)	1238.3	1872.4	963.3
Arunachal Pradesh (28.09377°, 094.592133°)	894	1320	716.3
Assam (26.407384°, 093.25513°)	1012.4	1522.6	859.4
Bihar (25.644085°, 085.906508°)	1076.1	1707	948.9
Chhattisgarh (21.663736°, 081.840635°)	1443.9	1896.2	895.8
Goa (15.300454°, 074.085513°)	1343	1887.8	927.6
Gujarat (22.385005°, 071.745261°)	1773.8	2021.2	830.2
Haryana (29°, 076°)	1251.8	1771.8	930.1
Himachal Pradesh (31.81676°, 077.349321°)	1312.8	1515.9	590.7
Jharkhand (23.455981°, 085.25573°)	1438	1860.6	879.6
Karnataka (14.52039°, 075.722352°)	1499.5	1967.4	900.1
Kerala (10.352874°, 076.51204°)	1112.3	1770.8	946.6
Madhya Pradesh (23.814342°, 077.534072°)	1504.9	1903.1	882.2
Maharashtra (18.906836°, 075.674158°)	1396.3	1929.3	944.2
Manipur (24.720882°, 093.922939°)	1350.3	1711.7	816.1
Meghalaya (25.537943°, 091.29991°)	1192.7	1628.3	856.1
Mizoram (23.214617°, 092.868761°)	1223.3	1697.5	824
Nagaland (26.163056°, 094.588491°)	1057	1506.7	804.4
Odisha (20.543124°, 084.689732°)	1268.4	1793.6	889
Punjab (30.929321°, 075.500484°)	1250.8	1738.8	906.1
Rajasthan (26.810578°, 073.768455°)	1763.8	2002	847.3
Sikkim (27.601029°, 088.454136°)	505.7	992.8	605.5
Tamil Nadu (10.909433°, 078.366535°)	1427.3	2027.2	957.6
Telangana (17.849592°, 079.115166°)	1453.3	1948.8	915.5
Tripura (23.775082°, 091.702509°)	1134.6	1696.1	911
Uttarakhand (30.041738°, 079.089691°)	1674.6	1772.3	702.8
Uttar Pradesh (27.130334°, 080.859666°)	1201.2	1763.3	931.5
West Bengal (22.996495°, 087.685588°)	1120.3	1758.2	959.1
UNION TERRITORIES			
Chandigarh (30.729844°, 076.784146°)	1290.2	1718.8	865.2
Dadra and Nagar Haveli and Daman and Diu (20.273395°, 073.004498°)	1466.1	1906.5	895.4
Delhi (28.627393°, 077.171695°)	1163.5	1717.8	923.2
Jammu and Kashmir (32.808885°, 074.913276°)	1309.4	1703.7	850.8
Andaman and Nicobar Islands (12.652888°, 092.779661°)	1292.2	1818.8	873.7
Ladakh (33.945641°, 077.656858°)	1375.5	1572.1	656.8
Puducherry (10.915649°, 079.806949°)	1410.1	1993.8	939.5
Lakshadweep (10.333731°, 072.920539°)	1394.6	1974.2	931.4

Table 1 Solar Irradiation Data (Global Solar Atlas 2024)

ii. **Solar PV module efficiency data***:*

The Solar PV module efficiency most importantly depends on the type of solar cell used in the system. The efficiency of solar cells combines with the layout of the panel and appropriate cleaning techniques to form Solar module efficiency. Fig.3.1 shows the best solar cells for efficiency, with data provided by the National Renewable Energy Laboratory (NREL). Though there are many emerging and exciting solar technologies underway, including Perovskite cells and Organic cells, the most commonly used cell technology in India remains silicon Crystalline cells, along with Thin-film technologies and Amorphous Silicon technologies finding their use as well. Therefore, these technologies will be the main focus of this study.

Noting from the data below, the main range of Solar PV efficiency that we will use to calculate will be 15% - 30% (lowest - Amorphous Si - 14%, highest - Single Crystal Si Cell - 27.6%).

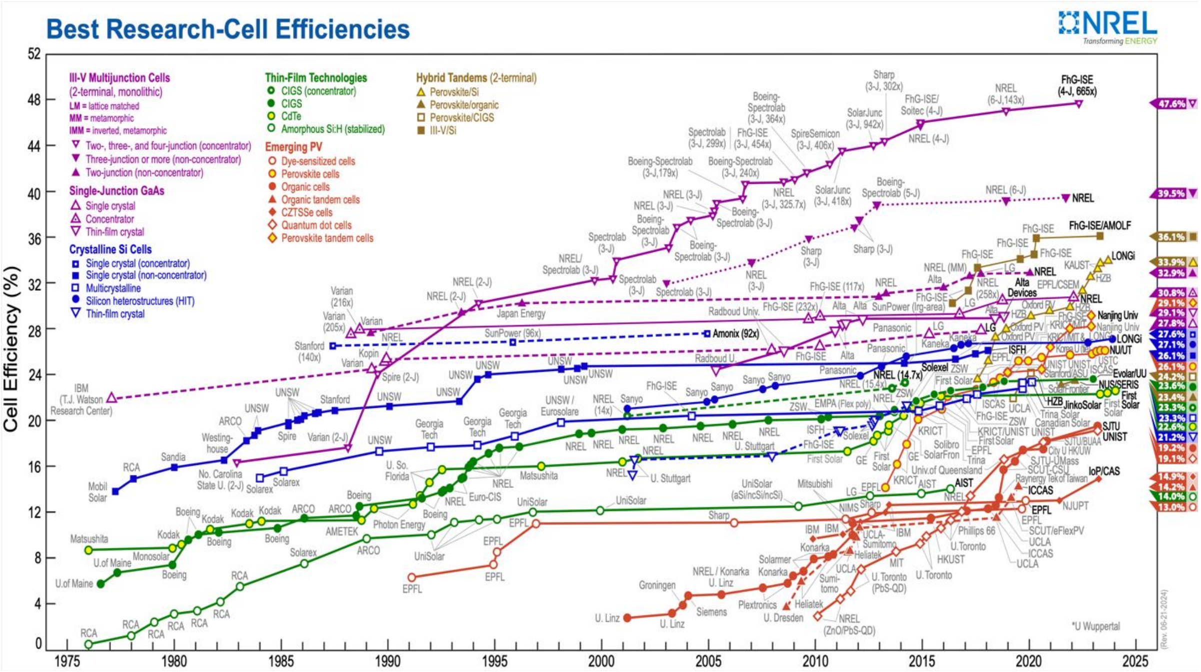

Figure 3.1 Solar Cell Efficiencies by NREL (NREL 2024)

iii. Payback Period:

The payback period is the amount of time it takes to recover the cost of an investment. Simply put, it is the length of time an investment reaches a breakeven point. Determining the payback period is useful for anyone and can be done by dividing the initial investment by the average cash flows, represented by the formula:

Payback Period = Initial investment / Cash flow per year

People and corporations mainly invest their money to get paid back, which is why the payback period is so important. In essence, the shorter the payback an investment has, the more attractive it becomes.

In case of Solar PV projects, the cash flows would be in the form of savings made on electricity consumption that the solar installation enables us to make. These savings would vary with varying electricity rates and differing PV module efficiencies.

In our method, we are calculating the Pay-back period while taking the following constants:

- System Capacity (kW) - 5 kW,
- Cost Per kW ($) - 2500$,
- System Size per kW (m2/kW) - 10 m2/kW,
- Solar Irradiation (kWh/m2) - Data from Table 1

And following variables:

- Electricity Rates ($/kWh)

- Solar PV module Efficiency

We further calculate the following:
- Total System Cost ($) = System Size * Cost per kW = 12500$,
- Total System Size (m2) = System Size per kW * System Capacity = 50 m2,
- Total Annual Production (kWh) = Solar Irradiation * Total System Size,
- Total Annual Savings ($) = Total Annual Production * Electricity Rate * PV module efficiency

Finally, we arrive at the following calculation:

- Payback Period (years) = Total System Cost / Total Annual Savings.

iv. *Levelized Cost of Electricity (LCOE):*
The Levelized Cost of Electricity (LCOE) is the net present value of the life cycle cost of the project divided by electricity production over the lifetime of the project. It can be seen as the production price of electricity adjusted over the lifetime of the project, and can be represented by the simple formula:
LCOE = total lifetime cost / total lifetime energy production
The levelized cost of electricity (LCOE) is often described as the benchmarking or ranking tool to assess the cost-effectiveness of different energy generation technologies, removing biases between the technologies. The method considers the lifetime generated energy and costs to estimate a price per unit of energy generated. The less a system costs and the more energy it produces, the lower the LCOE. The LCOE represents the price point at which the energy is to be sold to achieve a zero NPV. LCOE can be affected by financial parameters such as capital cost, depreciation, cost of debt, cost of equity and annual operating cost (which also includes spare part replacement cost & fuel cost). In the case of solar, it is affected by technical parameters such as plant efficiency, plant capacity factor, and plant degradation rate.

This study has employed the formula found in the study "Fraunhofer ISE – Levelized cost of electricity: Renewable Energy Technologies" for calculating LCOE (Dr. Christoph Kost 2021):
Input data assumed for this study are mentioned in the following Table 2.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

LCOE Levelized Cost of Electricity in EUR/kWh
I_0 Investment expenditure in EUR
A_t Annual total cost in EUR per year t
$M_{t,el}$ Produced amount of electricity in kWh per year
i Real interest rate in %
n Economic lifetime in years
t Year of lifetime (1, 2, …n)

Input data assumed for this study are mentioned in the following Table 2.

Technical and Financial Specifications	Data
Capital Cost in $ (I_0)	1,000,000 $
Operational Life in years (t)	20
Annual Operation and Maintenance Cost in $ (A_t)	1000$
Discount Rate (i)	0.05
Hours per Year	8760
Capacity Factor	0.5
Solar Irradiation per year in kWh/m^2	Data from Table 1
Solar PV Efficiency	0.15, 0.20, 0.25, 0.30
System Capacity in kW	1000

Using these inputs, the following are further calculated:
- Operating Hours per Year = Hours per Year * Capacity factor
- Annual System Capacity in kWh = System Capacity in kW * Operating Hours per Year

- Annual Electricity Generation ($M_{t,el}$) = Solar Irradiation * Annual System Capacity* Solar PV efficiency

All these factors finally are used to calculate the LCOE in (MWh/$) for Solar PV installations in different regions of India.

IV. Results and Discussion

This study has calculated the payback period and LCOE of all 36 states and Union territories of India employing the above-mentioned data and methodology. However, for the ease of convenience for the reader, the study is only showing results for the regions with the highest solar potential, i.e., regions with the shortest pay-back period and lowest LCOE, key attractors for project developers, to lay special emphasis on these regions rich in solar resource. Therefore, the results for the top 8 regions with the highest cost-effectiveness of Solar projects are:

i. Payback Period

The Payback period for the 8 different regions is represented graphically, as a function of the Electricity Rate with four different graphs for each region, representing different PV module efficiencies.

1) Chhattisgarh

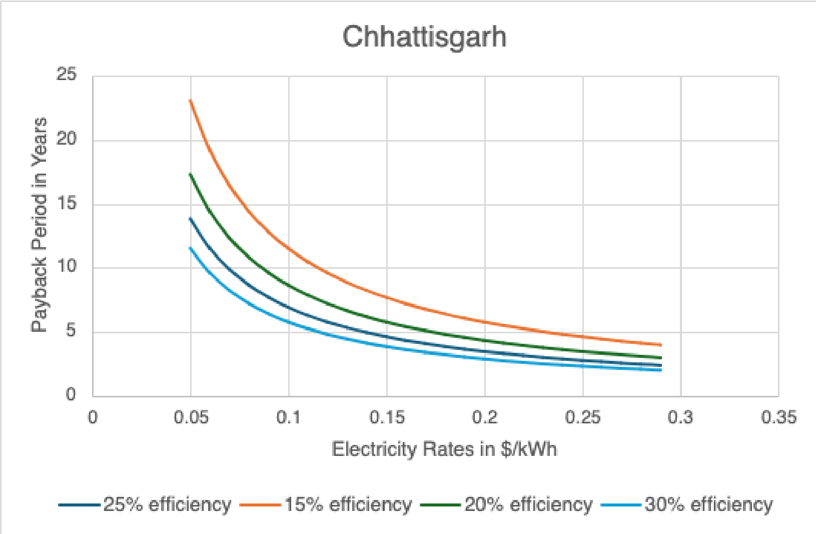

Figure 4.1

2) Gujarat

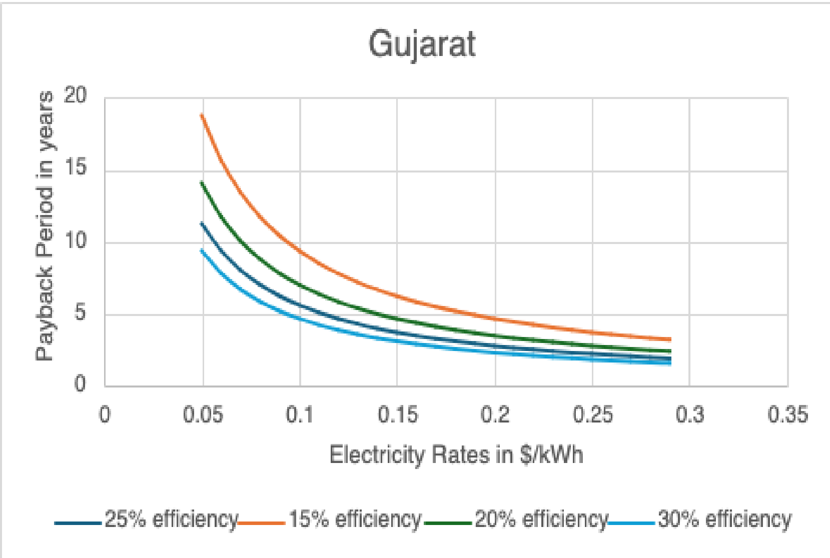

Figure 4.2

3) Karnataka

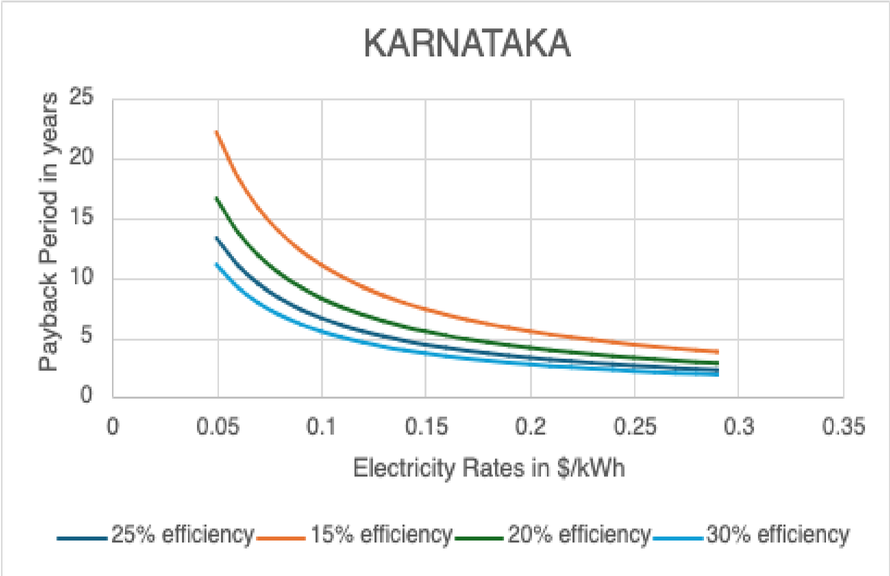

Figure 4.3

4) Madhya Pradesh

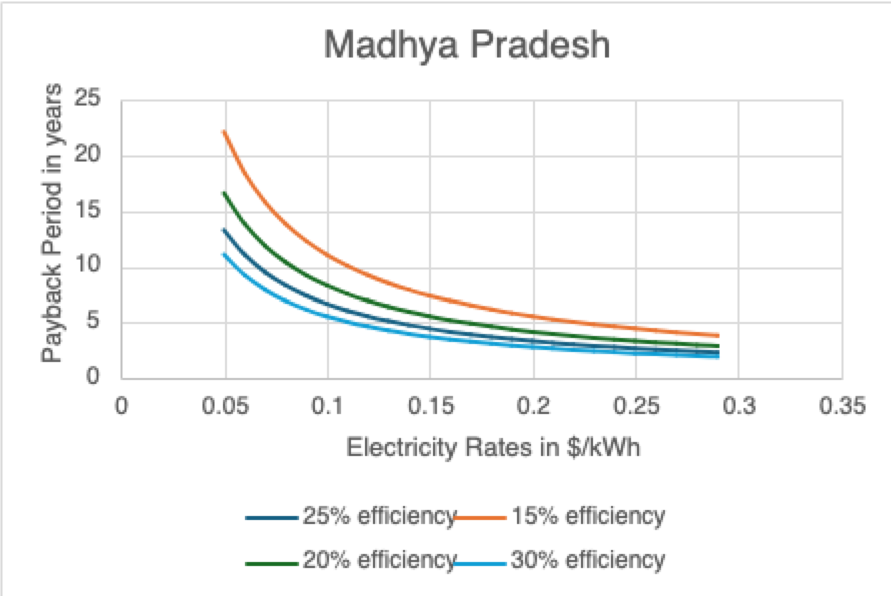

Figure 4.4

5) **Rajasthan**

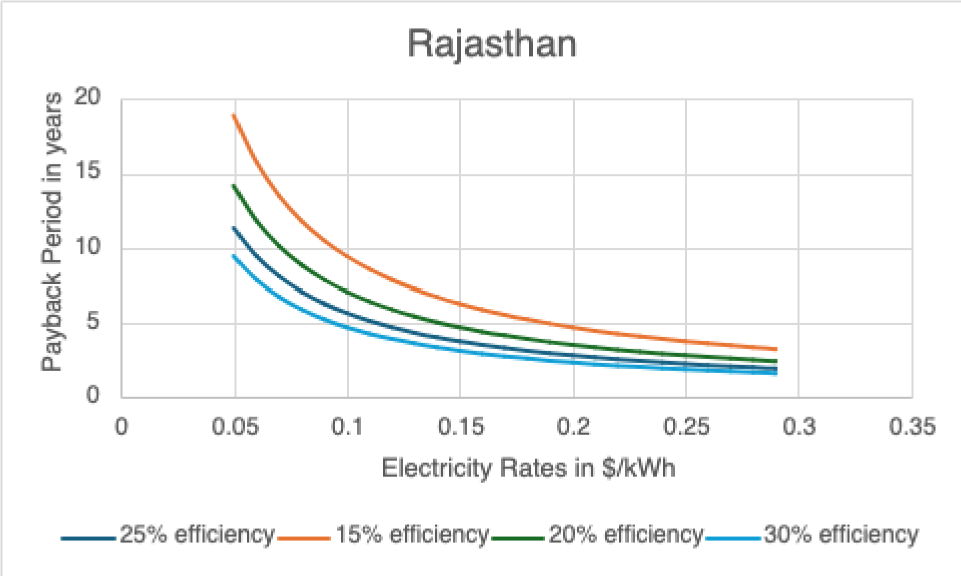

Figure 4.5

6) **Tamil Nadu**

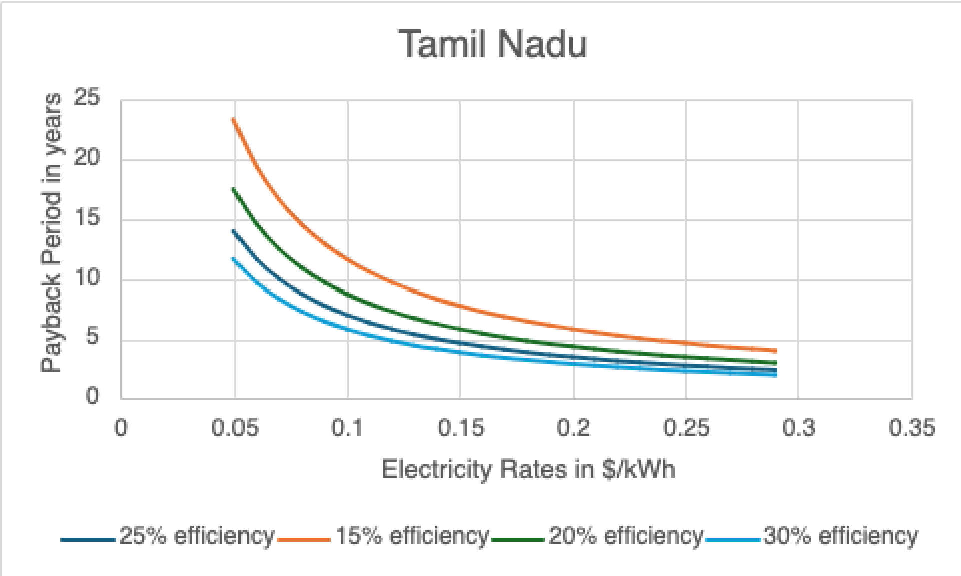

Figure 4.6

7) **Telangana**

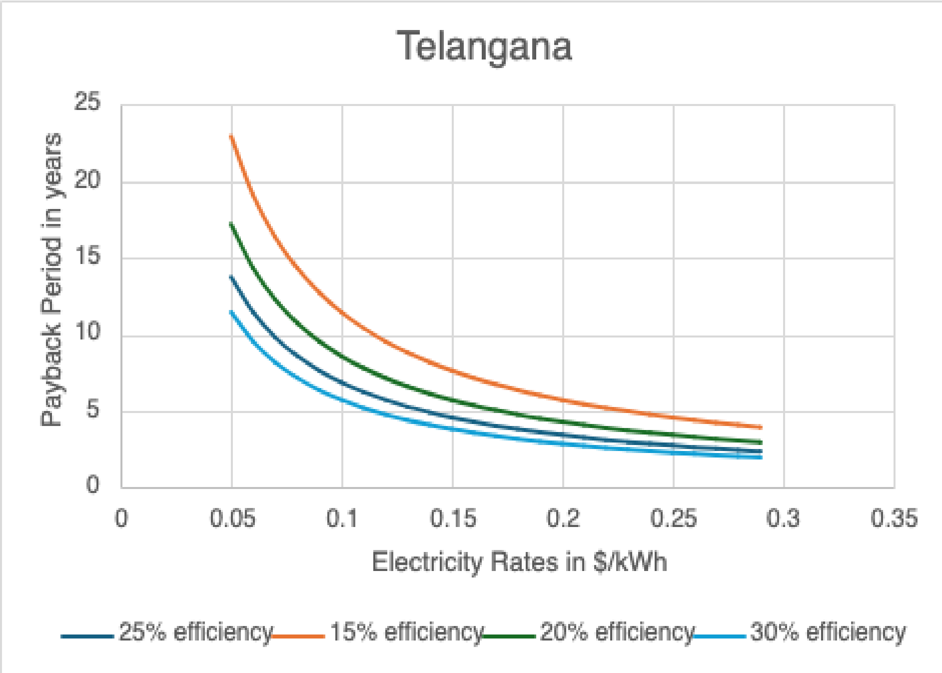

Figure 4.7

8) **Uttarakhand**

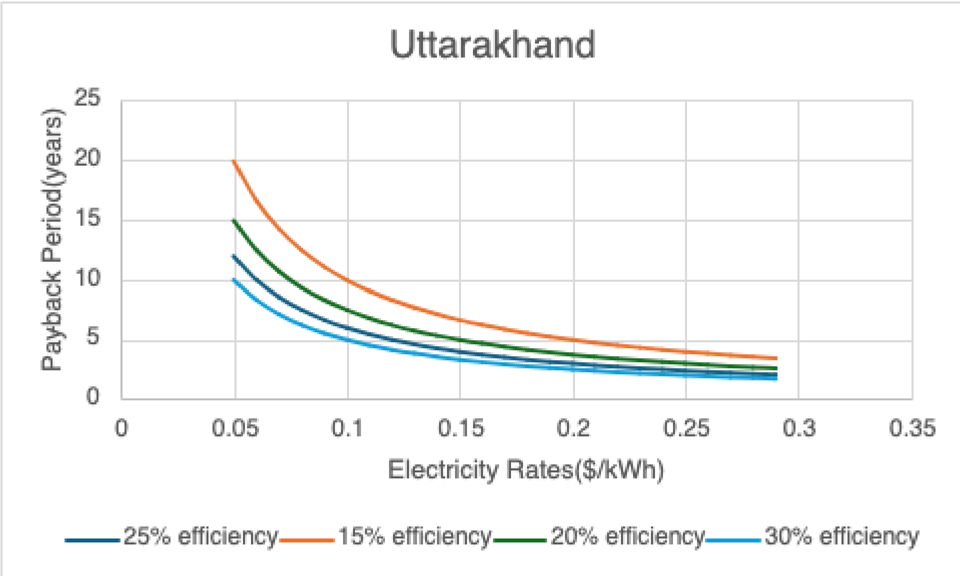

Figure 4.8

From the acquired results, we can see that as the electricity rates levied for electricity from the grid increase, the Solar project in turn saves more and leads to a shorter pay-back period for the investor, with payback periods reducing to lower than even 5 years for higher electricity rates.

- The results also show that as efficiency increases, the payback period for the project decreases significantly, even at the same electricity rates. This encourages project developers to use high-yielding, highly efficient Solar cells to increase their economic output. This is in line with government initiatives like the

Production Linked Incentive Scheme (PLI) introduced by the Central Government for the National Programme on High-Efficiency Solar PV Modules for achieving manufacturing capacity of Giga Watt (GW) scale in High-Efficiency Solar PV modules with an outlay of INR 24,000 Cr to boost domestic manufacturing and solidify India's position as a solar powerhouse (Invest India 2023).

- On a broader level, the Payback period is shorter at all efficiencies with state with greater Solar Irradiation resource. Thus, the initial phases of Solar development in India must take place in these regions to provide a positive upthrust to the sector and achieve maximum economic gain.

ii. LCOE Levelized Cost of Electricity

The results for the LCOE have been represented in the form of 4 graphs, for differing PV module efficiencies. Each graph is a bar graph depicting the LCOE (in $/MWh) of Solar PV projects in the 8 different regions based on the module efficiency.

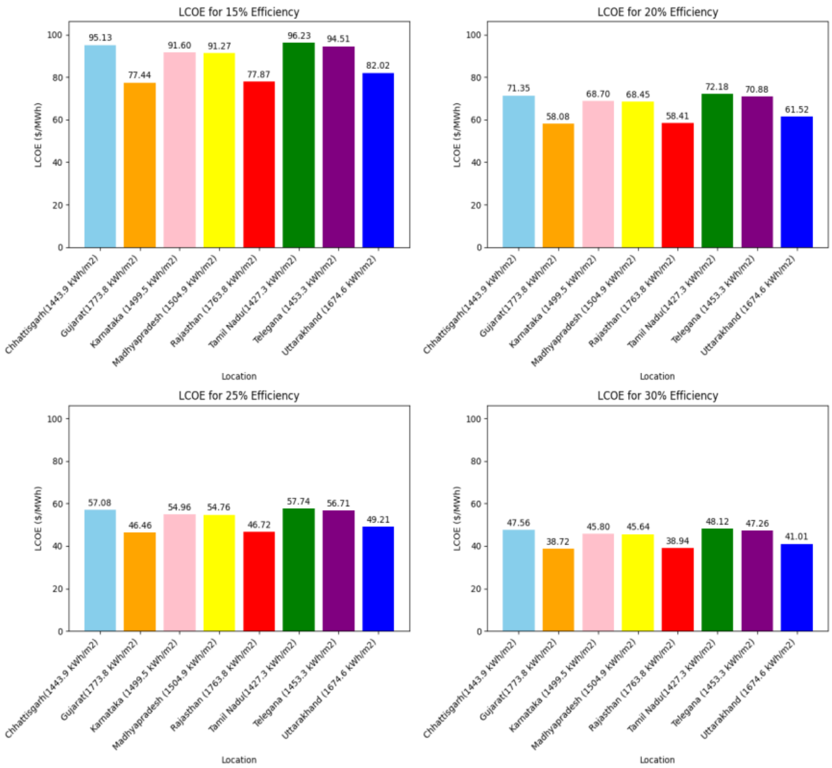

Figure 4.9

- The results show us that the LCOE decreases significantly as the cell efficiency increases. The LCOE will come down to even below the 49$/MWh global LCOE average for Solar PV in 2022(INREA 2023), in most solar resource-rich states of India if the cell efficiency increases to 30%, as depicted in the graph. This, again, encourages project developers to employ highly efficient solar panels which will lead to greater financial gain.
- The LCOE of solar projects are already comparable to that of Coal in India, the largest contributor to India's energy mix. According to reports by the IEA, the LCOE of Solar PV in India is going to reduce even further up till 2040, while the LCOE will stagnate (IEA 2019). This will result in a huge incentive for industries and homes to shift to solar PV.
- In these states, with high solar resources, these LCOE calculations will help people to compare different energy technologies with Solar PV without any biases and come to an informed decision.
- These results are also in line with global reports like that from IRENA, depicting the decreasing costs of Solar PV with increasing efficiencies and advanced technologies each year. Solar PV, which was 710% more expensive than the cheapest fossil fuel-fired solution in 2010 costs 29% less than the cheapest fossil fuel-fired solution in 2022 (IRENA 2023).

V. Conclusion

The Indian Government is bullish on achieving its target of installing 500 GW of renewable energy capacity by 2030 and is flushing out considerable amounts of money to do so, increasing the budget allocated to

MNRE more than twofold in 2024-25. The majority of this budget is being allocated to Solar energy projects (MNRE India Budget 2024-25). These economic resources must be utilized judiciously to achieve maximum financial output. This paper intends to present techno-economic metrics that compare the economic output of Solar PV projects in different parts of India, allowing policymakers and project developers to compare Solar PV with other energy resources and aiding them in their decision-making process. The study involves the calculation of the Payback Period and Levelized Cost of Electricity for Solar PV projects in different parts of India, which are internationally established methods to compare the economic output of energy projects. The results have been graphically represented for the top eight regions of India with the highest solar potential. The payback period has been presented as a function of varying electricity rates for four module efficiencies - 15%, 20%, 25%, and 30%, for each region. Similarly, the LCOE has been presented as bar graphs for each region, for the same set of PV module efficiencies. The results indicate that, with increasing technological advancements leading to greater solar cell efficiencies and by positioning the solar projects in the appropriate regions, the cost of Solar PV can be brought down significantly. Such efforts would lead to an India that is carbon neutral, independent of imports for its energy needs, has increased energy security and can provide its residents with clean, affordable and reliable energy.

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