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Rapid Decarbonization Roadmap for India Based on Photovoltaic Systems

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Abstract – According to the Paris Agreement signed by national leaders, the rapid decarbonization roadmap is critical for many citizens worldwide. The burden of saving the climate at acceptable levels urges national energy planning activities accordingly. Currently, India has a fossil fuel dominated power system with a rapid increase in renewable energy installations, namely photovoltaic, in the amount of 10 GW per year. India aims to reach 500 GW of installed electricity capacity from non-fossil fuel sources by 2030. This is a very ambitious target, which would require appropriate planning studies for judicious integration and optimal management of the system. Using Energy PLAN (advanced energy system analysis computer model), the authors created various scenarios involving the integration of the above-mentioned renewable energy based capacities into India's power system. It will provide key insights into the effects of certain policies and scenarios on the future overall energy balance, as well as the environmental (namely CO_2 emissions) and social impact, thus enabling more effective policymaking in this key dimension.

Index Terms – Rapid Decarbonization, Photovoltaic Systems, Renewable Energy, EnergyPlan

I Introduction

India's power system is a pivotal component of its economic growth, catering to the escalating energy demands driven by rapid industrialization and urbanization. The country's commitment to sustainable development is reflected in its ambitious renewable energy targets, aimed at reducing carbon emissions and enhancing energy security.

India has one of the largest power systems globally, with an installed capacity of approximately 441.3 GW as of 2023. This capacity includes 242 GW from fossil fuels, 8.1 GW from nuclear power, and 190 GW from renewable energy sources. India's renewable electricity generation stands at about 359.8 BU, sourced from solar, hydropower, wind, biomass, and other sources. India has set an ambitious goal of achieving 500 GW of installed electricity capacity from non-fossil fuel sources by 2030. This is a very ambitious target, which requires appropriate planning studies for judicious integration and optimal management of the system [1]. The transition towards renewable energy sources poses significant challenges in terms of energy management and grid stability. Existing systems often lack the necessary tools to effectively integrate variable renewable energy sources like solar and wind [2].

The primary objective of this paper is to analyse India's current share in renewable electricity generation, the installed capacity of various renewable sources, and the projected targets for 2030. Using the Energy PLAN model, this study compares the renewable energy shares for 2023 and 2030. With the help of different scenarios we will see how solar photovoltaic (PV) capacity affects the country's net CO_2 emissions.

II Literature Review

While a multitude of references are available in the literature, we have carefully selected a few that bear particular significance, in order to provide a more focused and nuanced analysis.

Population of India is growing at rapid pace along with its energy demand; this has caused greenhouse gas emissions to rise drastically. It's estimated that in the next years, energy exhaustion and GHG emissions might increase by 37%. Solar photovoltaic is being used to meet the nation's enormous increase in energy consumption. India now has one of the fastest-growing industries both domestically and internationally thanks to the manufacture and installation of PV systems. But effective deployment of PV technology in India faces some obstacles which includes low capacity utilization factor of PV plant [3].

Complete energy system, including the demands for industry, transportation, heating, cooling, and electricity, should be examined by the energy system analysis tool. Moreover, prospective system effects of system integration can be examined by doing hourly analysis over the full year. To guarantee that the entire energy system transitions to renewable energy, the planners and researchers should select an energy system analysis tool like EnergyPlan that can perform these tasks [4].

India can become 100% renewable energy based by 2050. This system will be mostly based on solar PV with battery storage. Batteries will be used to provide power supply when needed [5]. India's fully sustainable electrical grid will be based mostly on solar photovoltaic cells and batteries. In addition, prosumers will play an important role by contributing to the power generation. By maximizing their self-consumption, PV prosumers in India can significantly lower their annual electricity expenses. Levelized cost of energy for India's fully sustainable energy system in 2050 are estimated to be 52 €/MWh for the power and 46 €/MWh for the integrated scenarios [6].

Bjelic et. al. (2020) has obtained results for various regions by simulating various flexibility options for smooth penetration of variable renewable energy. They have used sector coupling

approach for managing variability. Large-scale PV and wind energy integration should be followed globally by electrification. Sector coupling is important for achieving net zero carbon system for example coupling of transportation sector with power generation sector. Hourly energy balance is ensured by simulation, meaning that production and consumption are equal throughout each hour. Consequently, each plant type's actual capacity factors are obtained.

Power generation from solar photovoltaic system produces less than one-fourth of greenhouse gases in comparison to that of fossil fuel-based steam turbine power generation [4].

Accurate assessment of real-time data is essential for long-term energy predictions. Potential errors and the lack of necessary data are the prominent limiting factors that affects the forecasting model's accuracy [7].

Global economic fluctuations can affect long-term energy predictions. Recessions and economic booms are examples of such external economic events that might affect energy pricing and demand, creating uncertainties that affect the forecasting accuracy [4].

Research shows that while commitment to rapid decarbonization at the national level generally indicate a favourable growth trajectory, but there are some distributive effects on GDP and employment [3].

III Theoretical Background

Energy PLAN can function in both economic and technical simulation modes. We have used technical simulation in this investigation. Energy PLAN prioritizes units according to fuel efficiency while making maximum use of locally produced energy. This means that the need for electricity is first met by VRE (variable renewable energy) source power plants, followed by combined heat and power plants, and at last by electricity imports, and power plants [8]. Energy PLAN has been proven for use in long-term energy planning exercises [9] among many other tools i.e. [10].

Due to the country's high solar irradiance profile and 290–300 days of sunshine each year, India has a very large potential for solar energy. Because of this there is continuous growth in installation of solar photovoltaic systems. India has set a target of 280 GW of solar PV capacity by the year of 2030. For such high target in long-term planning exercises all possible realizations of PV including the rooftop mounted [11] share [12] should be explored.

A Installed Capacity and Generation till 2023

As of 2023, the distribution of India's power generation capacity is as follows [13]:

Table 1. Distribution of India's generation capacity

Sources	Capacity (MW)	CUF	Generation (GWh)
Fossil fuels	242,617	0.62	1,323,580
Nuclear	8,180	0.67	47,817
Renewable	190,572	0.21	359,810

Source: India Climate and Energy Dashboard (ICED), NITI aayog (Apex public policy think tank of the Government of India) [11][13]

Contribution of Renewable Energy Sources is as follows:

- Solar Energy is the leading contributor to India's renewable energy mix, with an installed capacity of around 81,813 MW and a generation of 115,975 GWh. India's geographical location offers abundant solar potential, and the government has implemented various policies to promote solar energy deployment;
- Wind Energy is the second-largest contributor, with an installed capacity of 45,886 MW and generating 83,307 GWh. India's favourable wind conditions, particularly in coastal and high-altitude regions, support substantial wind energy production;
- Hydropower projects contribute 46928 MW of installed capacity and generate 134,053 GWh. These projects are vital for providing energy to remote and hilly areas;
- Biomass energy, including biogas and waste-to-energy projects, has an installed capacity of 10,941 MW and generates 16,989 GWh. Biomass utilization is significant in rural areas, where agricultural residues and organic waste are plentiful.

The projected renewable energy mix for 2030 involves (Table 2):

- Solar Energy- India is projected to install over 280 GW of solar capacity by 2030. This ambitious target aligns with India's commitment to increase the share of renewable energy in its total energy mix and reduce carbon emissions.
- Wind Energy - India aims to achieve around 140 GW of wind power capacity by 2030. This target is part of the broader goal to achieve 500 GW of total renewable energy capacity from non-fossil fuel sources by 2030.
- Hydro - Ministry of Power has outlined plans to increase the total installed hydro capacity to around 70 GW by 2030. This includes both large hydro projects and small hydro projects. As of 2023, India's installed hydro capacity stands at approximately 46.85 GW, indicating a planned addition of about 23.15 GW over the next seven years.
- Biomass - India's target of 10 GW of biomass installed capacity has already been achieved.

Table 2. Distribution of India's renewable capacity

Sources	Capacity (MW)	CUF	Generation (GWh)
Solar	81,813	0.16	115,975
Wind	45,886	0.21	83,307
Hydro	46,928	0.33	134,053
Biomass	10,941	0.18	16,989

Source: India Climate and Energy Dashboard (ICED), NITI aayog (Apex public policy think tank of the Government of India) [11][13]

Target of 500 GW for year 2030 will have a major share of solar PV that is 280 GW, which is more than half of the set target. This is due to the fact that it is easy to set-up solar plant in comparison to other sources.

B Future Renewable Energy Target (2030)

India aims to achieve 500 GW of installed capacity from non-fossil fuel sources by 2030 [13]. This target includes significant expansions in solar, wind, and other renewable energy capacities.

Table 3. Projected renewable energy mix

Sources	Target (GW)
Solar	280
Wind	140
Hydro	70
Biomass	10

Source: Central Electricity Authority (CEA) [13]

IV Methodology

Energy PLAN is a deterministic model, meaning it always yields the same results when given the same input. General inputs include fuel, heating, and electricity demands, energy technology [14]. The model generates a variety of outputs, such as emissions, excess electricity, hourly or annual electricity generation, and economic variables.

Initially, the systems should be developed to fulfil their role in meeting the national target, in accordance with the guiding principle of the design of energy systems for sustainable future. Additionally, this needs to contribute to achieving global strategies [15].

A. Data Collection

Gathering data on current energy capacities, generation, and consumption patterns. In this research we have collected data of installed capacities and generations from different fuel sources from India Climate and Energy Dashboard (ICED) by NITI Aayog (Apex public policy think tank of the Government of India).

Firstly we have developed India's energy model for year 2023 from the collected data. After that we have developed the energy model for 2030 following the 500 GW target of India. For year 2030 data is referred from Central Electricity Authority (CEA) and Ministry of New Renewable Energy (MNRE).

B. Scenario Development

a) Creating scenarios for 2023 and 2030 based on projected capacities and generation targets. This involves the following:

- Demand input: Electricity demand is 1,531 TWh/year and 14 TWh/year is electricity required for transportation.
- Supply input: We enter installed capacity in 217,589 MW of fossil fuel-based plant along with plants efficiency.
- Variable Renewable Energy Input: Capacity of all renewable energy sources are entered along with the distribution profile. Distribution file contains hourly generation for a complete year, which means it contains 8,784 data points. Wind capacity is 32,848 MW, photovoltaic 82,637 MW, and river hydro is 21,500 MW.

b) Creating scenario of different solar PV capacity for 2030 of the following cases:

1. India is able to achieve 25% more than the target capacity which is 350 GW.
2. India falls short of target by 25% and is only able to achieve 210 GW in year 2030.
3. India falls short of target by 50% and is only able to achieve 140 GW in year 2030.

V Results

Simulation and Analysis: Model is run using run (screen) option to obtain the results.

A base scenario for 2023

This section presents the results for the energy model of year 2023. The analysis of the model suggests that among the 100% primary energy supply of India, 15.1% is provided by renewable energy sources. Renewable energy based generation is responsible for supplying 23.5% of total electricity demand of country which is equivalent to 385.07 TWh. CO_2 emissions associated comes out to be 1589 Mt.

Future energy for 2030

This section presents the results for the energy model of year 2030. This model shows that among the 100% primary energy supply of India, 24.2% will be contributed by renewable. It shows that renewable energy based generation will supply 45.4% of total electricity demand in 2030 which is equivalent to 1149 TWh.

Variation 1 25% more Solar PV capacity

In this section we examine a hypothetical case in which solar PV capacity exceeds the target of 280 GW in 2030 by 25%. Fig 1 shows that primary energy supply from renewable will be increased to 26%. From Fig 2 we can see that electricity generation from renewable sources will be 50.7%. Fig 3 shows that the carbon dioxide emission will be reduced to 1,525 Mt which is lower than the values of 2023.

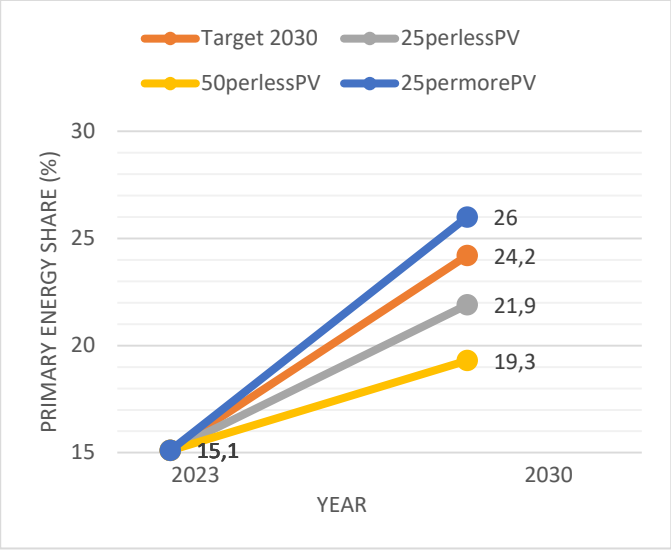

Fig 1. Primary energy share

Variation 2 25% less Solar PV capacity

In this section we examine the case in which India is able to achieve only 75% of targeted capacity of solar PV which is 210 GW by 2030. Fig 4 shows that the primary energy share of renewable sources has fallen to 21.9%. From Fig 5 we can see that contribution in electricity generation from renewable sources has also reduced to 39.2%.

Variation 3 50% less Solar PV capacity

This result is based on the model in which India achieves only 50% of targeted solar PV capacity by 2030 which is 140 GW. Fig 4 shows that the primary energy share of renewable sources has fallen to 19.3%. From Fig 5 we can see that contribution in electricity generation from renewable sources has reduced to 32.9%.

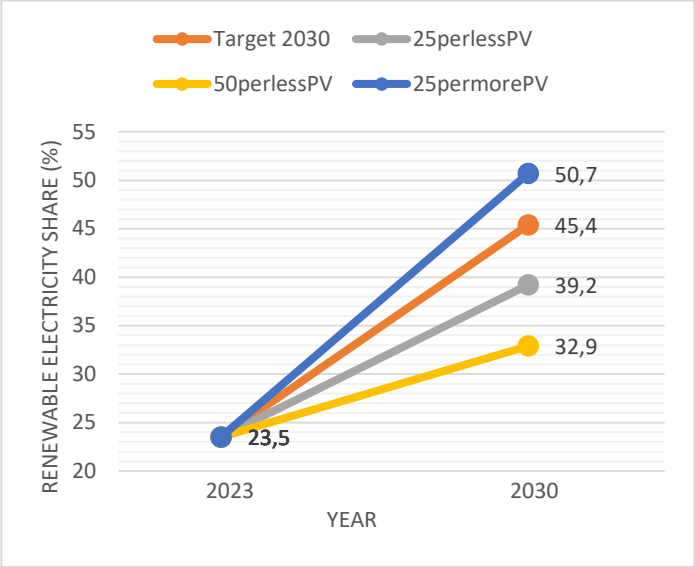

Fig 2. Renewable Electricity Share

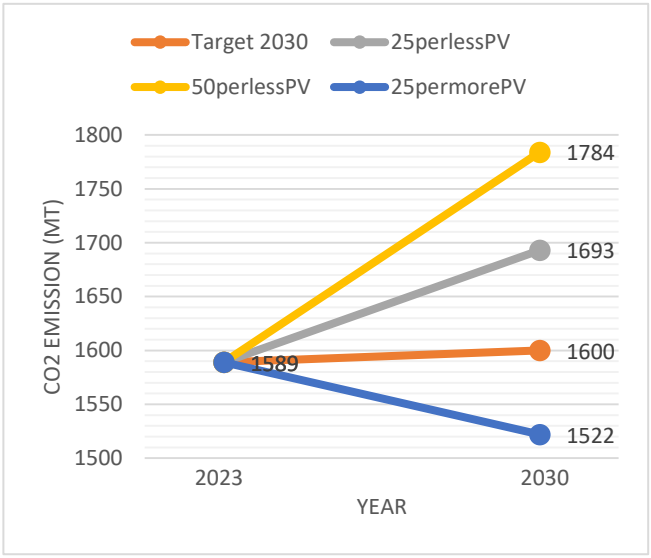

Fig 3. CO_2 Emission (Mt)

V Conclusion

Based on our study of different scenarios we have reached to following conclusions:

- Future scenario variant 1 for 2030 suggest that India will be able to meet 45.4% of its electricity demand from renewable generation sources. This is less than the target of 50% of renewable energy share set by Indian government.
- In case of 25% more Solar PV capacity installation, share of renewable electricity generation will be 50.7% which surpass the target of 50% set by Indian government for 2030.
- CO_2 emissions in 25% more solar PV model are the lowest among all the models, and comes out to be 1522 Mt. It is also lower than that of the year 2023. It shows that the installation of more solar photovoltaic can help India for its goal of rapid decarbonization.
- In 50% less PV model CO2 emission are the highest among all, which is 1784 Mt. This suggests that country's net carbon emission and solar PV concentration are related.
- From the three solar PV scenarios it is concluded that CO_2 emissions increase with decrease in solar PV capacity and is found highest in the scenario of 50% less solar PV model, and lowest in 25% more PV model.
- By analysis of all the scenarios we can see how important solar photovoltaic are for lowering CO_2 emissions and moving India closer to a low-carbon future. The differences in amount of CO_2 emission reveal the unique challenges and opportunities that India has to overcome in order to achieve rapid decarbonisation. For the purpose of creating efficient energy policies, policymakers, energy planners, and interested parties will find this comparison analysis to be an invaluable tool.

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Mapa puta brze dekarbonizacije Indije bazirana na fotonaponskim sistemima

Rezime **-** Prema Pariskom sporazumu koji su potpisali nacionalni lideri, mapa puta brze dekarbonizacije je kritična za mnoge građane širom sveta. Teret očuvanja klime na prihvatljivom nivou podstiče aktivnosti nacionalnog energetskog planiranja u skladu s tim. Trenutno Indija ima energetski sistem kojim dominiraju fosilna goriva sa brzim porastom instalacija obnovljivih izvora energije, odnosno fotonaponskih, u količini od 10 GW godišnje. Indija ima za cilj da do 2030. dostigne 500 GW instalirane električne energije iz obnovljivih izvora. Ovo je veoma ambiciozan cilj, koji bi zahtevao odgovarajuće studije planiranja za razumnu integraciju i optimalno upravljanje sistemom. Koristeći Energy PLAN (kompjuterski model za naprednu analizu energetskog sistema), autori su kreirali različite scenarije koji uključuju integraciju gore navedenih kapaciteta zasnovanih na obnovljivoj energiji u indijski elektroenergetski sistem. Ovo će pružiti ključni uvid u efekte određenih politika i scenarija na budući ukupni energetski bilans, kao i uticaj na životnu sredinu (odnosno emisije CO_2) i društveni uticaj, čime će se omogućiti efikasnije kreiranje politike u ovoj ključnoj dimenziji.

Ključne reči - brza dekarbonizacija, fotonaponski sistemi, obnovljivi izvori energije, EnergyPlan