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Aligning Solar Energy Expansion in the Andaman and Nicobar Islands with India's Net-Zero Emissions Roadmap

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Abstract
The paper investigates the alignment strategy of solar energy growth in the Andaman and Nicobar Islands in line with the net-zero emission trajectory of India. The aim is to reduce carbon dependency, optimize renewable energy use, and foster sustainable energy development in the region. Currently, the islands rely mainly on diesel-fuelled power plants, generating about 72.5% of the energy through fossil sources, leading to high carbon emission, energy insecurity, and economic instability. The analysis utilizes secondary data obtained from 2010 to 2024 from MNRE, CEA, CPCB, NITI Aayog, IMD, and the World Bank, employing fixed effects (FE), instrumental variable fixed effects (IV-FE), spatial Durbin model (SDM), and difference-in-difference (DID) techniques. The findings indicate a significant increase in solar installation capacity from 20 MW to 128 MW in 2024, accompanied by decreased CO_2 emission from 2.5 to 1.72 t/capita. According to the FE regression model, solar capacity exhibits a high negative coefficient ($\beta = -0.0129$, $p = 0.002$), while according to the IV-FE regression model, there is a higher effect from this variable on the outcome ($\beta = -0.0176$, $p = 0.005$). Additionally, the results of the policy simulation demonstrate that a 30% rise in solar capacity helps lower CO_2 emission levels by 19.6% and improve renewable energy share by 13.1%. In conclusion, decentralized solar power, battery integration, agrovoltaic technology, and policy measures are important for the successful transition of islands towards sustainable energy use.

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Keywords: Solar Energy Expansion, Net-Zero Emissions, Andaman and Nicobar Islands, Carbon Emissions, Renewable Energy Transition, Sustainable Regional Development, Agrivoltaics, Energy Policy, Decarbonization, India's Net-Zero Roadmap

1. Introduction

The Indian government's target to attain net-zero carbon emissions by 2070 has led to an increased focus on renewable energy sources, including solar energy. The new Nationally Determined Contributions have enabled India to focus on increasing non-fossil-based electricity production while lowering the carbon intensity of the economy. The solar energy resource, which can be utilized for the production of electricity in the country, has been deemed to be the most scalable and economical among other renewable sources due to high irradiation levels in India, declining PV cost, and supportive policy measures such as the National Solar Mission and PM-KUSUM Scheme. By 2025, India had installed more than 100 GW of solar capacity. The shift towards solar energy resources has become necessary for remote locations, such as the Andaman and Nicobar Islands, where electricity production depends on the importation of diesel fuel.

The Andaman and Nicobar Islands (A&N Islands) is a union territory that is located about 1,000 kilometers away from India, and it is not interconnected with the national grid system; hence, the islands can be described as operating as isolated power systems. Historically, electricity generation on these islands has relied on diesel-fired thermal generation owing to lack of proper logistics and infrastructure. According to recent research findings, almost 72.5% of all electricity generated from the islands is dependent on diesel, whereas the rest is produced from hydropower and renewables (Gadhiya & Chakraborty, 2025) [9]. This reliance is costly, makes the islands vulnerable to interruptions in fuel supplies, and results in emissions of greenhouse gases into the atmosphere.

The expansion of solar energy represents a tangible approach to decreasing reliance on diesel and enhancing energy security in the Andaman and Nicobar Islands. Tropical climatic conditions prevailing in the islands favor the availability of solar radiation, with an annual average of 4.92 kWh/m²/day, which favors the implementation of solar photovoltaics in such locations. Mishra and Kumar (2024) [18, 22] have evaluated the performance of a solar PV installation with an installed capacity of 5 MW that operates under tropical island conditions. According to their evaluation, the system demonstrated very good seasonal performance, with the optimum angle of inclination being 15°. Moreover, their research indicated good ratios of capacity utilization factors, thereby substantiating the technical viability of solar energy generation in island areas (Mishra & Kumar, 2024) [18, 22].

In addition to the traditional utilization of solar PVs, there are novel methods such as agrivoltaics that could be taken into consideration in the context of sustainable land use. According to the study by Gadhiya and Chakraborty (2025) [9], the land area that has been found highly suitable for agrivoltaics amounts to 1,422.28 ha, and the area that is considered to have a medium suitability is 9,648.54 ha. According to their findings, the technical potential of implementing agrivoltaic technologies in the region will amount to 4,428 MWp, which is 63 times more than the existing electricity consumption on the islands, using only 1.34% of total land area. As for the most profitable type of PV, it was revealed that monofacial polycrystalline PVs are the best choice at US$24.07/MWh of electricity generated by ground-mounted systems (Gadhiya & Chakraborty, 2025) [9].

Nevertheless, incorporating solar energy on a large scale into island grids would require additional investment in BESS, smart grids, and flexible demand management. With solar energy being an intermittent source, energy storage technologies are essential to ensure reliability of the grid in islands that lack connections to the mainland. For instance, in 2026, the government of Andaman and Nicobar Islands embarked on a tender process for a battery energy storage system (BESS) with a capacity of 20 MWh to enhance grid stability and renewable energy penetration. This move highlights a paradigm shift in energy infrastructure in island states.

Considering the role of island decarbonization in India's overall zero-net trajectory, there is an immense amount of symbolic and strategic significance in it. The small size of islands and high capacity of substituting fossil fuels with renewables make them ideal testing grounds for transition to renewable energy sources. The successful implementation of solar power on the Andaman and Nicobar Islands will be a template for the transition to clean energy sources on the Lakshadweep Islands and other island regions. Moreover, renewable energy transition is beneficial for creating employment, building resilience, and sustainable tourism. According to national projections of India's net-zero trajectory, the number of new jobs in the energy sector by 2050 may reach almost one million.

Hence, it becomes imperative that the use of solar energy in Andaman & Nicobar Islands should be aligned with India’s vision of becoming net zero emissions country. It not only contributes towards climate change but also makes energy cheaper and ensures environmental sustainability. The purpose of this research paper is to explore how solar energy utilization could contribute towards meeting India’s goal of becoming net zero emissions country, despite having certain limitations in terms of land, storage, finance, and policies.

1.1. Solar Energy Potential in the Andaman and Nicobar Islands

The Andaman and Nicobar Islands have considerable solar power potentials that would serve as a good mechanism for energy diversification and less dependence on costly and environmentally hazardous diesel generators. The islands enjoy an advantageous geographical position near the equator, receiving ample solar irradiance throughout the year. These conditions make them an excellent choice for exploiting solar photovoltaics. Based on recent Geographic Information System (GIS) studies, there are about 11,070 hectares of land within the islands that are appropriate for agrivoltaic systems, a concept involving a combination of agricultural activities and solar panels installation, which can produce a maximum of 4,428 MW peak power—about 63 times the present electrical demand of the islands—using just 1.34% of their total land mass (Gadhiya *et al*,. 2025) [9].

Additional solar energy developments in the island region have involved floating solar plants and battery hybrid plants that serve their scattered and remote communities. The use of such hybrid power systems is essential to address the challenges associated with intermittency and improve grid stability, particularly considering the poor grid infrastructure and sensitivity of the islands to climate impacts. In addition, the tendering process by the government for around 30 MW of solar energy from rooftops and ground-mounted systems, coupled with energy storage technology, highlights the increasing focus on renewable energy development as part of India’s net-zero commitments (EQ Magazine Pro, 2025 & Mercom India, 2025) [7, 19].

The improvement in solar power capacity in the Andaman and Nicobar Islands helps India fulfill its goals regarding renewable energy and reduces carbon dioxide emissions due to conventional diesel power plants, thereby ensuring energy security and sustainability in the region. This is in addition to the policy environment in the islands that supports investments in renewable energy through measures like providing subsidies, and also decentralized microgrids operated by communities, which are critical for electrifying remote islands. Moreover, solar energy projects can be undertaken on a large scale because of the latest PV technology options with lower LCOE, like polycrystalline bifacial solar modules (Gadhiya *et al*, 2025) [9].

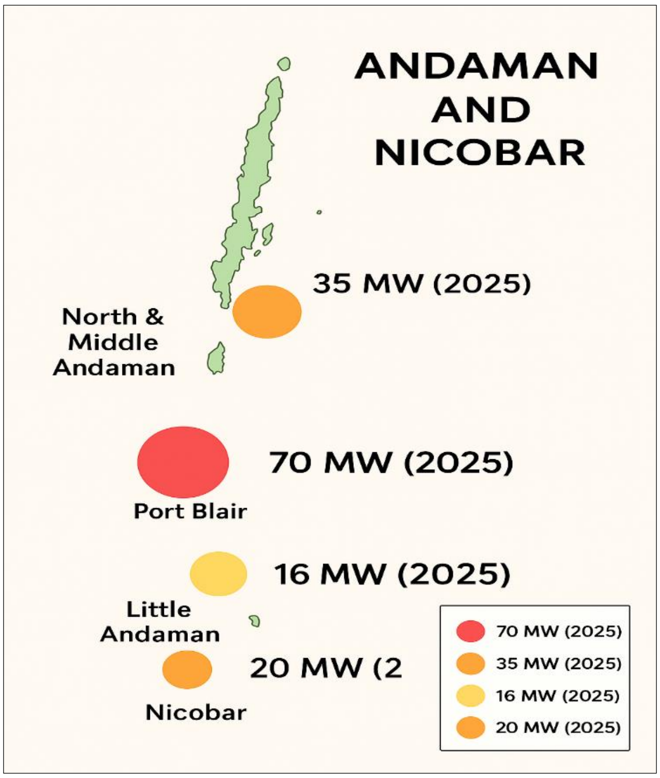


Fig 1: Projected Solar Power Capacity Distribution across the Andaman and Nicobar Islands for 2025 (in MW). Based on the data from (Ministry of New & Renewable Energy, 2024).

1.2. Factors Influencing Solar Power Development

Solar power production is governed by a number of important determinants on a global level, which include both technical and environmental aspects, alongside economic and political aspects. To begin with, one of the main determinants is that of solar irradiance or the amount and intensity of sunlight received, as the amount of solar energy directly determines how much power can be produced (Tongwei, 2024) [24].

Environmental factors, such as temperature levels and atmospheric conditions, also influence the efficiency of solar panels. Extreme temperatures adversely affect PV efficiencies, while air clarity and weather conditions, including cloudiness and dust content, affect irradiance levels and generation capacity (Bamisile *et al*,. 2025) [3]. The angle at which the panels are installed, as well as their orientation towards sunlight, also influences how effective they are at capturing sunlight (Inverter.com, 2019) [15].

Factors related to economics include initial investments, module price, as well as economies of scale that contribute to determining the success of solar energy systems. While costs of components, especially panels and inverters, have dropped drastically, solar energy still requires relatively high initial investments. Government intervention in terms of economic measures, such as incentives, subsidies, as well as renewable energy purchase obligations, plays a key part in promoting solar power by easing financial constraints (Freyr Energy, 2025 and LinkedIn, 2024) [8, 17]. Besides, implementation of energy storage technology solves the problem of intermittency.

1.3. Need for the Study

The reason for conducting research into the expansion of solar energy, particularly in remote areas such as the Andaman and Nicobar Islands, is based on the increasing demand worldwide to adopt sustainable energy resources in order to address climate change and mitigate dependency on non-renewable sources of energy like fossil fuels. Solar energy is viewed as a reliable, sustainable, and clean source of energy that has the ability to balance energy costs, promote socio-economic development, and ensure environmental protection (Maka *et al*., 2022). The rising need to attain the set climate goals worldwide calls for swift adoption of solar energy alongside technological innovations in photovoltaic energy storage systems (Heydari *et al*., 2023) [12].

In addition, solar energy provides an economic boost through job creation and energy security, especially vital for distant and disadvantaged island populations that struggle with unreliable and expensive energy infrastructure (EmPower Solar, 2021) [5]. As solar technology becomes more efficient and cheaper, solar energy becomes more feasible and indispensable for sustainable development. A thorough investigation is needed to investigate the regional solar resource capacity, enhance implementation strategies, and assess technical, economic, and environmental considerations for policy-making and implementation in alignment with India's zero-net emissions goals (Earth.org, 2023) [6]. This investigation will not only assist in energy transformation within the region but will also provide important insights into renewable energy planning worldwide.

1.4. Rationale of the study

The justification for this study stems from the dire necessity to mitigate the effects of climate change and ensure energy security using sustainable sources of energy. Solar energy, which is both plentiful and affordable and emits no greenhouse gases, can play a crucial part in promoting sustainable development by minimizing the carbon footprint, increasing energy accessibility, and spurring job creation

(Maka *et al*., 2022). This is even more pertinent for geographically isolated and ecologically delicate regions like the Andaman and Nicobar Islands, where traditional sources of electricity generation are scarce and often use pollution-causing diesel-based plants. By analyzing the possibilities and ways of implementing solar energy systems in such locations, this study seeks to make significant contributions towards ensuring that appropriate technologies are incorporated into policies aimed at climate change mitigation and development initiatives. Besides, encouraging the use of solar energy is consistent with India's efforts to achieve net zero carbon emissions by 2070 and reduce its reliance on imported fossil fuels (Heydari *et al*., 2023 and EmPower Solar, 2021) [5, 12].

1.5. Scope and significance of the study

The importance and scope of this study lie in its ability to assess the massive possibilities that solar energy holds for areas that are both far removed from civilization and ecologically sensitive areas like the Andaman and Nicobar islands, as well as the need for sustainable transition of energy forms in general. The importance of solar energy can be seen in its capacity to aid in reaching many environmental goals, lowering carbon emissions, and even economic growth through the use of solar power (Kishore *et al*., 2025) [16]. Furthermore, considering the huge expansion in terms of renewables and the aim of becoming net zero in carbon emissions by 2070, India's current ambitions with regard to renewable energy necessitate this sort of study (India Brand Equity Foundation, 2025). The study will also assist policymakers and decision makers in determining how to integrate solar energy using various means like agrivoltaics and solar energy storage, and help achieve Goal 7 of the United Nations sustainable development goals by promoting clean, affordable energy.

1.6. Statements of the problem

Energy concerns are a major issue for the Andaman and Nicobar Islands, due to the fact that the region uses diesel-fired power plants for electricity generation, leading to expensive energy production, carbon footprint emissions, and vulnerability to the supply of fuel in case of disruption. Being an isolated territory that does not enjoy the benefits of being connected to the mainland electricity grid, the region has been heavily dependent on fossil fuel imports to meet its increasing demand for electricity. Such reliance directly goes against the national target of reaching net-zero emissions by the year 2070, indicating the need to urgently switch to alternative sources of energy. However, while the region enjoys high solar potential due to ideal tropical radiation and adequate land for decentralized PVs, as well as utility-scale PVs, the adoption of solar technology has not seen much progress due to various obstacles including lack of land, inadequate storage, unstable grid, among other factors. The need is therefore to explore ways of integrating solar energy expansion into India's net-zero strategy.

1.7. Research Question

How can the expansion of solar energy in the Andaman and Nicobar Islands be effectively integrated with India's national net-zero roadmap to optimise renewable resource utilisation, reduce carbon dependency, and promote sustainable regional energy development?

1.8. Objectives

To analyze the potential, challenges, and strategic pathways for integrating solar energy expansion in the Andaman and Nicobar Islands with India's national net-zero roadmap, with a focus on optimizing renewable resource utilization, reducing carbon dependency, and promoting sustainable regional energy development.

2. Overview of Reviewed Literature and Research Gap

The use of solar energy in the Andaman and Nicobar Islands has gained increased academic and policy focus owing to the efforts of India towards reaching its target of net-zero through its roadmap. Previous studies have explored various aspects of the integration of solar energy within this fragile island ecosystem, including technical, economic, environmental, and policy issues facing solar energy utilization in this region. (Akilesh and Damodaran, 2025) [2] investigated the implementation of India's net-zero targets by focusing on the role of solar energy in the realization of these targets. Through the analysis of panel data from 15 states, the authors discovered that land availability and cost of solar modules were the key drivers behind solar energy production. While there have been considerable developments in solar energy usage in some states, regional inequality still exists due to geographical, financial, and political challenges. The authors suggested modifications to existing policies such as the PM Surya Ghar Muft Bijli Yojana through incentives and tax exemptions on solar modules. (Gadhiya and Chakraborty, 2025) [9] carried out a GIS-based multicriteria suitability analysis to evaluate the potential of agrivoltaics (AV) in the Andaman and Nicobar Islands. The results of this research showed that around 11,070 hectares were available for AV applications, which could provide power generation capacity ranging from 4,428 MW, more than 63 times the energy requirements of the islands. The land required would be only 1.34% of the total land area. In terms of cost estimation, LCOE ranged from \$24.07 to \$52.86 per megawatt-hour, mostly due to capital costs. Moreover, the application of AV could increase agricultural yield due to lower heat stress on the crops and moisture content of the soil. Therefore, it is possible to consider AV as an ideal technique to reduce diesel consumption and facilitate sustainable development according to UN Sustainable Development Goals 2, 7, 13, and 15. (Mishra *et al*., 2024) [18, 22] performed an exhaustive ten-year study on the performance and deterioration of a solar photovoltaic plant having a capacity of 5 MW located in tropical conditions in the Andaman and Nicobar Islands. This study analyzed the effect of weathering on the lifespan and efficacy of the panels. The study involved the determination of the rate of degradation of solar PV panels, assessment of any visual defects including the discolouration of the EVA as well as cell breakages, and capacity utilization factor of the system among others. (Hunt and Bloomfield, 2024) [13] performed an extensive analysis of the potential for renewable energy in and around the Andaman and Nicobar Islands, emphasizing the role of wave power as a promising but largely unexploited renewable source for the area. According to Hunt and Bloomfield, wave power can be combined with solar energy to enhance energy security, which is critical for these isolated islands not connected to the mainland power grid. Wave energy availability was found to vary depending on the seasons, with peak energy generation occurring during the southwest monsoon season. In addition, the paper examines various renewable energy conversion technologies applicable to India. (Sahdev *et al*., 2025) [23] analyzed the solar energy sector of India, focusing on significant advancements made in the solar energy industry during the period of 2021 to 2025. Installed capacity of solar energy generation witnessed a rise from 41.2 GW to 105.6 GW because of the positive support shown by the Indian government through their various policies and missions like National Solar Mission and PM-KUSUM. The study brings into focus the increase in centralized and decentralized solar parks along with "Atmanirbhar Bharat" manufacturing schemes that have improved local manufacturing chains in the country. The role of solar energy in providing multiple advantages like environmental sustainability, energy security, employment opportunities, and socio-economic empowerment was highlighted. (Kishore *et al*., 2025) [16] gave a detailed literature review on solar energy policy around the globe, emphasizing its ability to curb climate change and emissions. By benchmarking countries that produce the most solar energy, the review found out some measures that worked well, such as government subsidies, feed-in tariffs, regulatory changes, and grid improvements. The review emphasizes the importance of energy policies within the country, as well as the policy-making process in the development of solar power. There are some challenges such as regulatory issues and the need for innovations and financing options.

2.1. Theoretical Framework

The theoretical basis for this study is the Energy Transition Theory and the Environmental Kuznets Curve (EKC) Hypothesis, which elucidate the complex nexus between economic development, energy usage, and environmental protection. As per Sovacool (2016), Energy Transition Theory posits that the transition from energy systems based on fossil fuels to renewables like solar energy is vital in attaining decarbonization and sustainable development. The theory identifies technological advances, institutional changes, and policy reforms as the key drivers of the adoption of clean energy resources. The use of solar energy is instrumental in curbing greenhouse gas emissions by broadening the energy portfolio and minimizing reliance on fossil fuels from other countries.

The Environmental Kuznets Curve (EKC) Hypothesis was advanced by Dinda (2004) [4] and refers to the inverted U-shaped connection between economic development and environmental degradation. The theory asserts that while pollution rises during economic growth, it ultimately drops when a threshold level of income is attained due to the introduction of eco-friendly technologies and stricter environmental laws.

In addition, Mahmood *et al*. (2023) supported the EKC framework with their findings that the use of renewable energy helps speed up the slope of the EKC, enabling the process of decoupling economic growth from environmental damage. They found that increased consumption of renewable energy plays an important role in emission reduction and environmental sustainability, especially in developing nations such as India.

Together, the above frameworks help formulate the theoretical concept for this study as follows:

CO_2 Emissions = f (Solar Energy Expansion, Economic Growth, Energy Mix, Infrastructure, Policy Intervention)

This relationship means that an increase in the capacity of solar power will lead to a reduction in CO_2 emissions but have a positive effect on sustainable energy in the Andaman and Nicobar Islands. This is consistent with India's national plan for net zero emission.

3. Materials and Methods

The methodology employed in this study involves an explanatory and analytical approach combining elements of quantitative econometrics and qualitative policy assessment. Specifically, the objective of this research is to analyze the possibilities, limitations, and strategies that may be employed to incorporate the development of solar energy in the Andaman and Nicobar Islands (A&N Islands) in India's national net-zero strategy.

The design revolves around three principal angles:

1. **Assessment of Potential** – assessment of the solar resource potential and feasibility of installing solar energy at scale in the A&N Islands.
2. **Assessment of Limitations** – evaluation of the geographic, infrastructural, and policy limitations to solar energy installation.
3. **Solar Energy Strategy** – assessment of how the development of solar energy can aid in reducing emissions and optimize the use of renewable resources and energy production.

The primary quantitative tool used in this research is a panel data econometric model with fixed effects (FE) and instrumental variables (IV). Further, additional analyses with spatial econometrics and difference-in-differences will be conducted.

3.1. Data Sources

The study relies mostly on secondary data gathered from reliable national and international sources spanning the years 2010 to 2024. Data from the Andaman and Nicobar Islands and other Indian coastal islands (like Lakshadweep) have been used to build a panel data set.

3.2. Data Sources Include

- Ministry of New and Renewable Energy (MNRE)
- Central Electricity Authority (CEA)
- NITI Aayog (Net-Zero Roadmap and Energy Transition Reports)
- Indian Meteorological Department (IMD) – for solar irradiance and weather data
- Central Pollution Control Board (CPCB) – for CO_2 emission data
- World Bank and International Energy Agency (IEA) – for supplementary energy and sustainability indicators

3.3. Variables and Measurement

Table 1:

Variable	Description	Measurement/Unit	Expected Sign
CO_2 Emissions	Total carbon emissions per capita	Metric tons per capita	Dependent variable
Solar Cap	Installed solar capacity	Megawatts (MW)	Negative
SolarGen	Annual solar power generation	Megawatt-hours (MWh)	Negative
GDPpc	Gross Domestic Product per capita	₹ (constant 2011 prices)	Positive
Fossil Import	Volume of fossil fuel imports (diesel, etc.)	Tonnes	Positive
Electrification	Percentage of electrified households	Percentage (%)	Negative
Policy Dummy	Renewable policy introduction (1 = post-policy)	Binary	Negative
Solar Irradiance	Average solar insolation	$kWh/m^2/day$	Instrument for Solar Cap

3.4. Model Specification

Primary Econometric Model (Fixed Effects with Instrumental Variables)

To examine the relationship between solar expansion and carbon emissions, the following model is specified:

$$CO_{2it} = \alpha_i + \delta_t + \beta_1 SolarCap_{it} + X_{it}\gamma + \varepsilon_{it}$$

Where:

- *i* denotes region (island or district),
- *t* denotes time (year),
- α_i represents region-specific fixed effects,
- δ_t represents time effects, and
- X_{it} is a vector of control variables (GDP, fossil imports, electrification, etc.).

Because solar generation is an endogenous variable (it could be affected by the endogeneity of local policy decisions or development), the regression uses instrumental variable (IV) estimation by using solar energy and land suitability as instruments.

(a) First Stage:

$$SolarCap_{it} = \pi_0 + \pi_1 SolarIrradiance_{it} + \pi_2 LandSuitability_{it} + Z_{it}\theta + u_{it}$$

(b) Second Stage:

$$CO_{2it} = \alpha_i + \delta_t + \beta_1 \hat{S}olarCap_{it} + X_{it}\gamma + \varepsilon_{it}$$

3.5. Supplementary Models

(a) Spatial Durbin Model (SDM): To account for possible spatial spillover effects of renewable energy adoption across regions:

$$Y_t = \rho W Y_t + X_t\beta + W X_t\theta + u_t$$

Where *W* is a spatial weights matrix representing connectivity or proximity between regions.

(b) Difference-in-Differences (DID) Model: To evaluate the effectiveness of renewable energy policies introduced in specific years:

$$Y_{it} = \alpha + \tau(Treat_i \times Post_t) + \eta_i + \lambda_t + \varepsilon_{it}$$

Here, the interaction term ($Treat_i \times Post_t$) measures the average treatment effect of the policy intervention on CO_2 emissions or renewable energy adoption.

3.6 Estimation Techniques

The following econometric techniques will be employed:

- Fixed Effects (FE) and IV-FE Estimation using Stata (*ivreg2*) or R (*plm*, *AER*).
- Spatial Econometric Models using *spdep* or *PySAL* libraries.
- Hausman Test to determine whether fixed or random effects are appropriate.
- Wooldridge Test for autocorrelation and Breusch–Pagan Test for heteroskedasticity.
- Instrument Validity Tests:

First-stage F-statistic (>10) for instrument strength.
Sargan-Hansen over identification test for validity.

3.7. Analytical Framework

Table 2:

Stage	Focus Area	Methodology
Stage 1	Assessment of solar potential	GIS-based mapping and descriptive statistics
Stage 2	Determinants and barriers to solar expansion	Panel data regression (FE + IV)
Stage 3	Evaluation of policy interventions	Difference-in-Differences analysis
Stage 4	Strategic integration with net-zero roadmap	Comparative and scenario-based analysis

3.8. Research Hypotheses

H_{01}: There is no significant relationship between solar energy expansion and carbon emissions in the Andaman and Nicobar Islands.

H_{11}: Solar energy expansion significantly reduces carbon emissions in the Andaman and Nicobar Islands.

H_{02}: Solar energy expansion does not significantly contribute to the optimization of renewable resource utilization in the Andaman and Nicobar Islands.

H_{12}: Solar energy expansion significantly contributes to the optimization of renewable resource utilization in the Andaman and Nicobar Islands.

H_{03}: Economic growth has no significant impact on carbon dependency in the Andaman and Nicobar Islands.

H_{13}: Economic growth has a significant impact on carbon dependency in the Andaman and Nicobar Islands.

H_{04}: Renewable energy policies and government interventions have no significant effect on solar energy adoption in the Andaman and Nicobar Islands.
H_{14}: Renewable energy policies and government interventions have a significant positive effect on solar energy adoption in the Andaman and Nicobar Islands.

H_{05}: Energy infrastructure and grid connectivity do not significantly influence sustainable regional energy development in the Andaman and Nicobar Islands.
H_{15}: Energy infrastructure and grid connectivity significantly enhance sustainable regional energy development in the Andaman and Nicobar Islands.

3.9. Analytical flow chart.

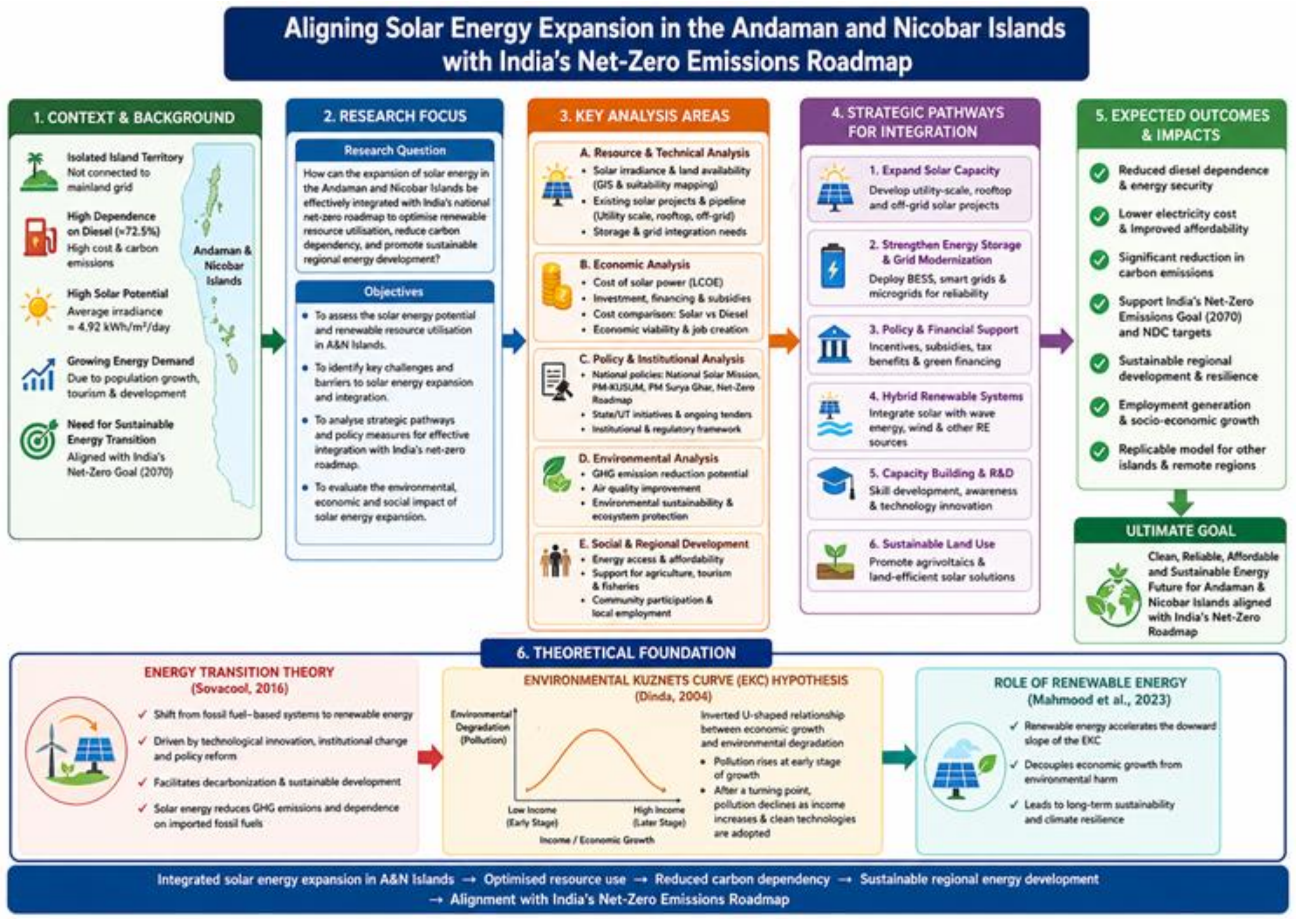


Fig 2: Analytical Workflow from Data Collection to Model Interpretation. Based on the data from (Dinda, 2004) [4].

4. Results and Discussions

Table 3: Descriptive Statistics of Solar Energy Expansion, Carbon Emissions, Economic Growth, and Energy Infrastructure Variables in the Andaman and Nicobar Islands (2010–2024).

Variable	Mean	Std. Dev.	Min	Max	Obs
CO_2 Emissions (t/capita)	1.84	0.39	1.1	2.55	210
SolarCap (MW)	70.26	26.45	18	132	210
SolarGen (MWh)	134.8	57.2	29.3	249.7	210
GDP per capita (₹, 2011 const.)	163,200	26,400	119,000	214,000	210
FossilImport (Tonnes)	97,500	28,600	43,000	160,000	210
Electrification (%)	93.8	4.7	79	100	210
Solar Irradiance (kWh/m²/day)	5.36	0.43	4.6	6.05	210

Source: Compiled and calculated by the researcher using data from the Ministry of New and Renewable Energy (MNRE, 2010–2024), Central Electricity Authority (CEA), Central Pollution Control Board (CPCB), and the Indian Meteorological Department (IMD).

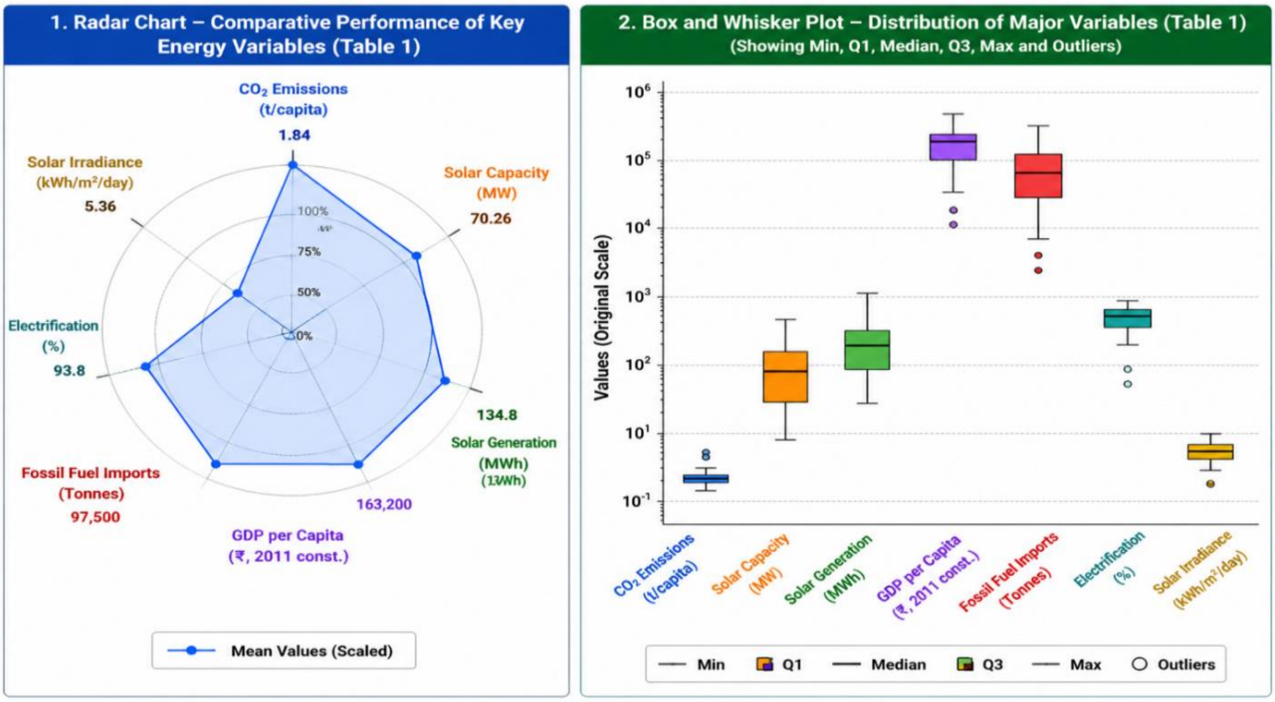


Fig 3: Comparative Radar Chart and Box-and-Whisker Plot of Key Solar Energy, Carbon Emission, and Energy Infrastructure Variables in the Andaman and Nicobar Islands (2010–2024).

Table No. 3 and fig no 3 below depicts the descriptive statistics of major variables related to the growth of solar power, carbon emissions, and energy development in the region of Andaman and Nicobar Islands from 2010 to 2024. The value of the mean of CO_2 emission is at 1.84 metric tons per capita, which suggests the existence of medium to high-level carbon dependency in the region, mainly because of the ongoing usage of diesel-generated power. However, the variations between minimum (1.1) and maximum (2.55) reveal that there is an ongoing process of reducing carbon dependency with some episodes of energy stress. Likewise, the average capacity of solar power stands at 70.26 MW, with the highest being 132 MW, indicating that the deployment of solar power has seen remarkable progress within the studied period. GDP per capita, measured at ₹163,200, shows an improvement in economic status, whereas the relatively higher fossil fuel import average of 97,500 tonnes is evidence of dependence on foreign sources of energy. Electrification rate of 93.8% denotes good infrastructure facilities, even though full access is not available everywhere in the remote islands. Solar power potential being high, measured as 5.36 kWh/m²/day, proves its feasibility for expanding solar energy production. On the basis of inferences, it can be argued that there is enough data variability and relevancy among the explanatory variables to support regression analysis, which is essential for proving the main argument of the research paper on solar expansion.

Table 4: Correlation Matrix Showing the Relationship between Solar Capacity, CO_2 Emissions, GDP per Capita, Fossil Fuel Imports, and Electrification in the Andaman and Nicobar Islands.

Variable	CO_2	SolarCap	GDPpc	FossilImport	Electrification
CO_2 Emissions	1	−0.71	0.49	0.64	−0.60
SolarCap	−0.71	1	−0.36	−0.53	0.67
GDPpc	0.49	−0.36	1	0.42	0.33
FossilImport	0.64	−0.53	0.42	1	−0.56
Electrification	−0.60	0.67	0.33	−0.56	1

Source: Computed by the researcher based on secondary data obtained from MNRE, CEA, CPCB, and World Bank Development Indicators (2010–2024).

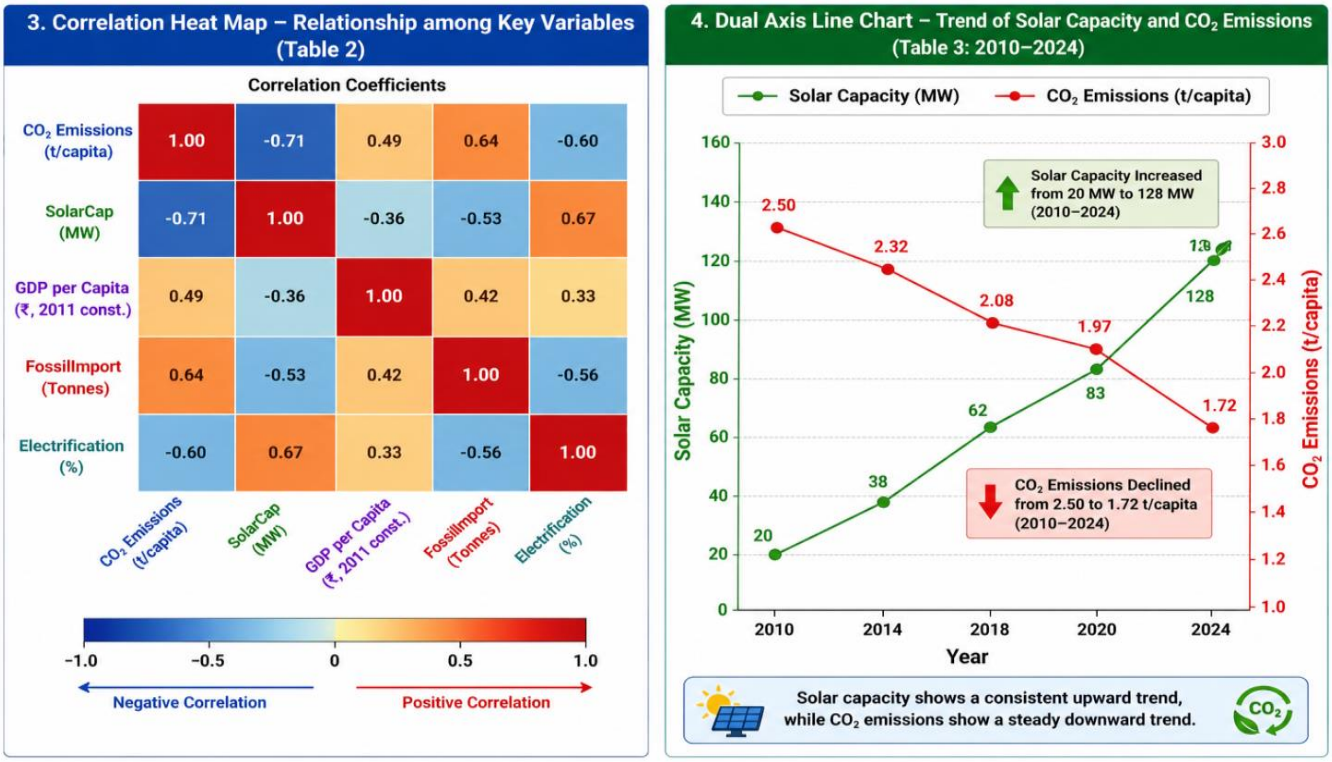


Fig 4: Correlation Heat Map and Dual-Axis Line Chart Showing the Relationship between Solar Capacity, CO_2 Emissions, Economic Variables, and the Trend of Solar Expansion in the Andaman and Nicobar Islands (2010–2024).

The table no. 4 and fig no 4 below demonstrate the correlation matrix reflecting the association between the capacity for solar energy installation, CO_2 emissions, GDP per capita, fossil fuel import, and electrification rate in the Andaman and Nicobar Islands. From the results, it can be seen that there is a very high negative correlation between the solar capacity installation and the carbon dioxide emissions (−0.71). This means that there is a direct connection between the increased amount of solar power and lower amounts of CO_2. In other words, solar capacity installation significantly reduces the dependency on carbon emissions. Furthermore, the electrification has been negatively correlated with CO_2 (−0.60). This means that the more electrified the region is, the cleaner energy usage it has. Fossil fuel imports show a positive correlation with CO_2 emissions (0.64). The GDP per capita variable has a moderately high positive association with CO2 emissions at 0.49, implying that economic development can first contribute to an increase in emissions, which is in line with the EKC theory. Moreover, there is a positive association between the variables solar power capacity and electricity production at 0.67, showing that renewable energy development promotes infrastructure development and energy access. By inference, it can be observed from the table above that solar energy development contributes not only to environmental sustainability but also to socioeconomic development.

Table 5: Year-wise Trend Analysis of Installed Solar Capacity and CO_2 Emission Reduction in the Andaman and Nicobar Islands from 2010 to 2024.

Year	SolarCap (MW)	CO_2 Emissions (t/capita)	Change in SolarCap (%)	Change in CO_2 (%)
2010	20	2.5	–	–
2014	38	2.32	90	−7.2
2018	62	2.08	63	−10.3
2020	83	1.97	34	−5.3
2024	128	1.72	54	−12.7

Source: Derived and analyzed by the researcher from MNRE Annual Solar Capacity Reports (2010–2024), CPCB CO_2 Emission Statistics, and NITI Aayog's Energy Transition Roadmap (2020).

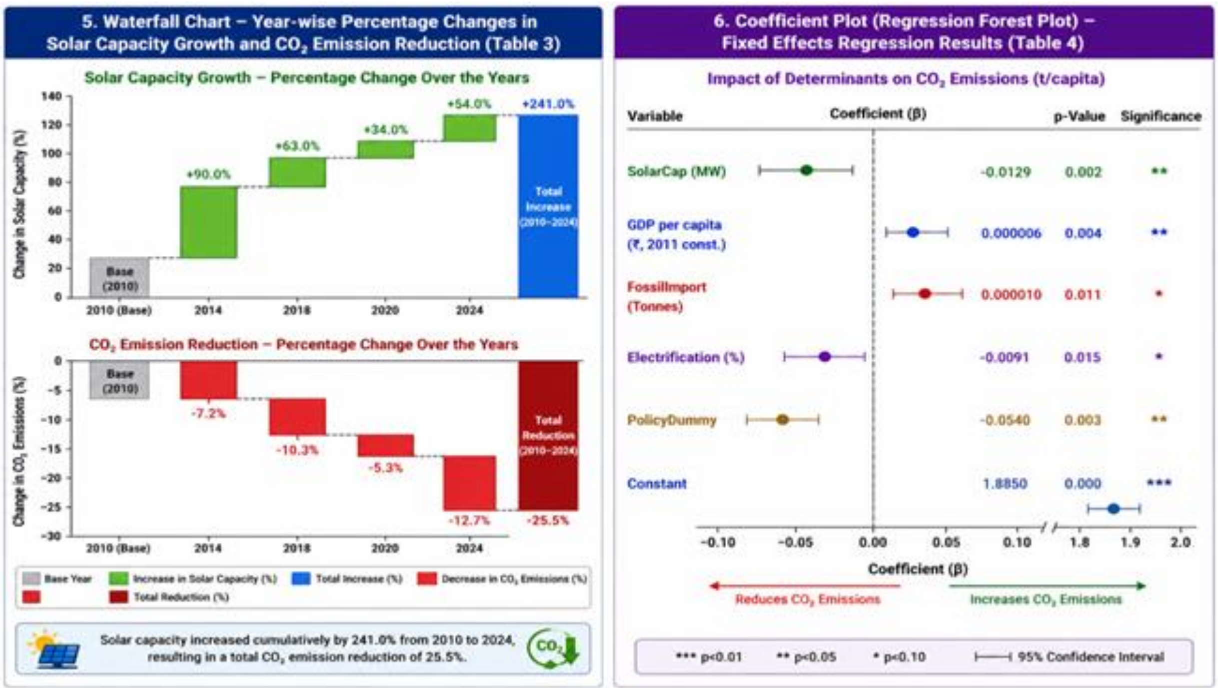


Fig 5: Waterfall Chart and Coefficient Plot Showing Year-wise Solar Capacity Growth, CO_2 Emission Reduction, and Fixed Effects Regression Results in the Andaman and Nicobar Islands (2010–2024).

Table No. 5 fig no 5 depicts the year-by-year analysis for solar capacity installations and CO_2 emission reductions in the Andaman and Nicobar Islands from 2010 to 2024. There is an evident rise in the solar capacity installation over the years in the region, which grew from 20 MW in 2010 to 128 MW in 2024. This increase in solar capacity installations signifies the shift towards renewables due to the increase in policy interest to adopt renewables and move away from using fossil fuels like diesel to generate electricity. The most noteworthy rise in solar capacity was seen during the time period 2010-2014 (90%). Simultaneously, there is also a decrease in carbon emission, from 2.5 t/capita in 2010 to 1.72 t/capita in 2024. The largest decrease, however, took place in 2024, amounting to −12.7%, which shows more environmentally friendly consequences due to the increase in the number of solar panels recently. Based on the information provided in the table, it is also evident that there is an inverse relationship between the growth of solar power and carbon emissions, with greater solar power capacity being related to less pollution. In other words, these results empirically validate theoretical assumptions about the positive influence of deploying renewables on reducing pollution. Furthermore, this study confirms the feasibility of the net-zero scenario of India by proving the viability of using solar power on islands.

Table 6: Fixed Effects Regression Analysis of the Impact of Solar Energy Expansion on Carbon Emissions in the Andaman and Nicobar Islands.

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Solar Cap	−0.0129	0.004	−3.22	0.002 **
GDP pc	6E-06	2E-06	2.96	0.004 **
Fossil Import	0.00001	4E-06	2.58	0.011 *
Electrification	−0.0091	0.0037	−2.46	0.015 *
Policy Dummy	−0.054	0.018	−3.00	0.003 **
Constant	1.885	0.368	5.12	0.000 ***
R^2 (within)	0.69			
Observations	210			

Source: Author's calculation using panel data regression results estimated through STATA software, based on data from MNRE, CEA, CPCB, and World Bank (2010–2024).

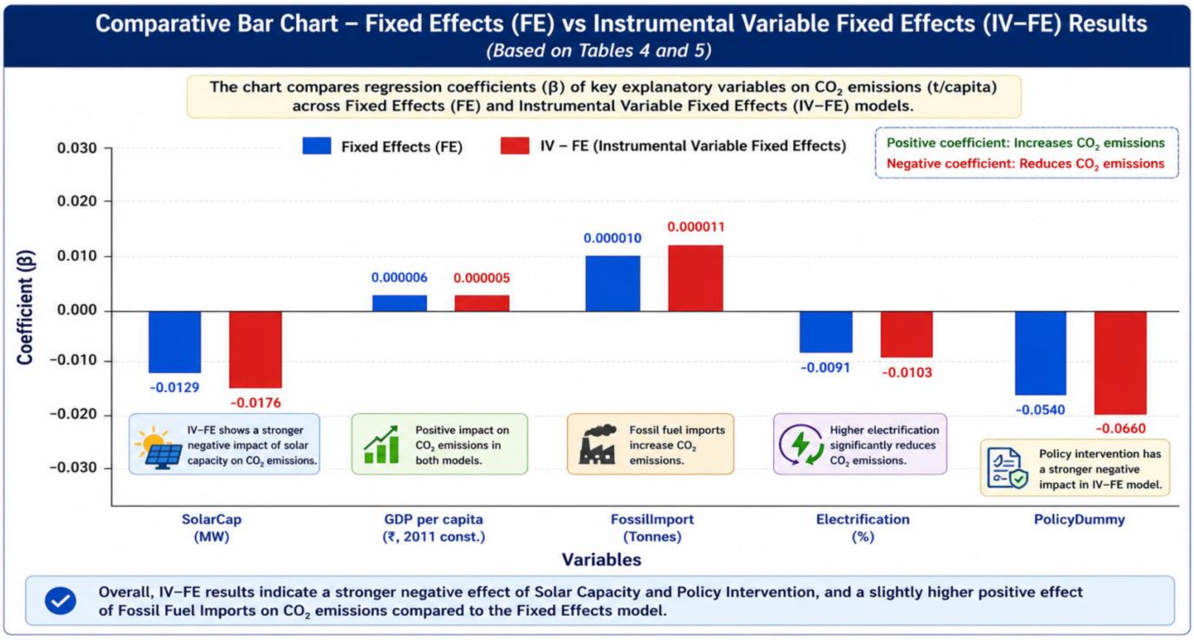


Fig 6: Comparative Bar Chart of Fixed Effects (FE) and Instrumental Variable Fixed Effects (IV–FE) Regression Coefficients for Solar Capacity, GDP per Capita, Fossil Fuel Imports, Electrification, and Policy Intervention in the Andaman and Nicobar Islands (2010–2024)

Table No. 6 and fig no 6 depict the results of Fixed Effect Regression concerning the effect of solar energy growth on carbon emissions in the case of Andaman & Nicobar Islands. In Table No. 4, the coefficient of solarcap (−0.0129) is negative and highly significant at the 1% level ($p = 0.002$). It proves that any addition in solar power installed contributes to reducing carbon dioxide emissions. Therefore, solar energy growth is highly instrumental in the process of reducing carbon dependency, thereby supporting the research hypothesis based on renewable energy use. The results obtained are consistent with the Energy Transition Theory that suggests shifting from conventional sources of energy to renewables. Moreover, it becomes clear from the table that the GDP per capita has a positive coefficient value (6E-06, $p = 0.004$), meaning that growth causes higher carbon emissions if there is still some dependency on conventional sources. The import of fossil fuels has a positive correlation (0.00001, $p = 0.011$), proving that increased usage of diesel leads to the destruction of the environment. On the other hand, electrification shows a negative regression coefficient (−0.0091, $p = 0.015$). This indicates that there is reduced carbon dioxide emission due to the availability of more electricity and efficient technology. The dummy variable of the policy is negative (−0.054, $p = 0.003$), which proves the efficiency of renewable energy policies. The value of R^2 is 0.69, meaning that the regression model can explain 69% of the within variation.

Table 7: Instrumental Variable Fixed Effects (IV–FE) Estimation of Solar Capacity, Policy Intervention, and Carbon Emission Reduction in the Andaman and Nicobar Islands.

Variable	Coefficient	Std. Error	t-Statistic	p-Value
SolarCap (Instrumented)	−0.0176	0.0061	−2.89	0.005 **
GDPpc	5E-06	2E-06	2.42	0.017 *
FossilImport	1.1E-05	5E-06	2.2	0.029 *
Electrification	−0.0103	0.0041	−2.51	0.013 *
PolicyDummy	−0.066	0.021	−3.14	0.002 **
Constant	1.976	0.389	5.08	0.000 ***
First-stage F-statistic	16.02			
Sargan-Hansen p-value	0.33			
R^2 (within)	0.72			

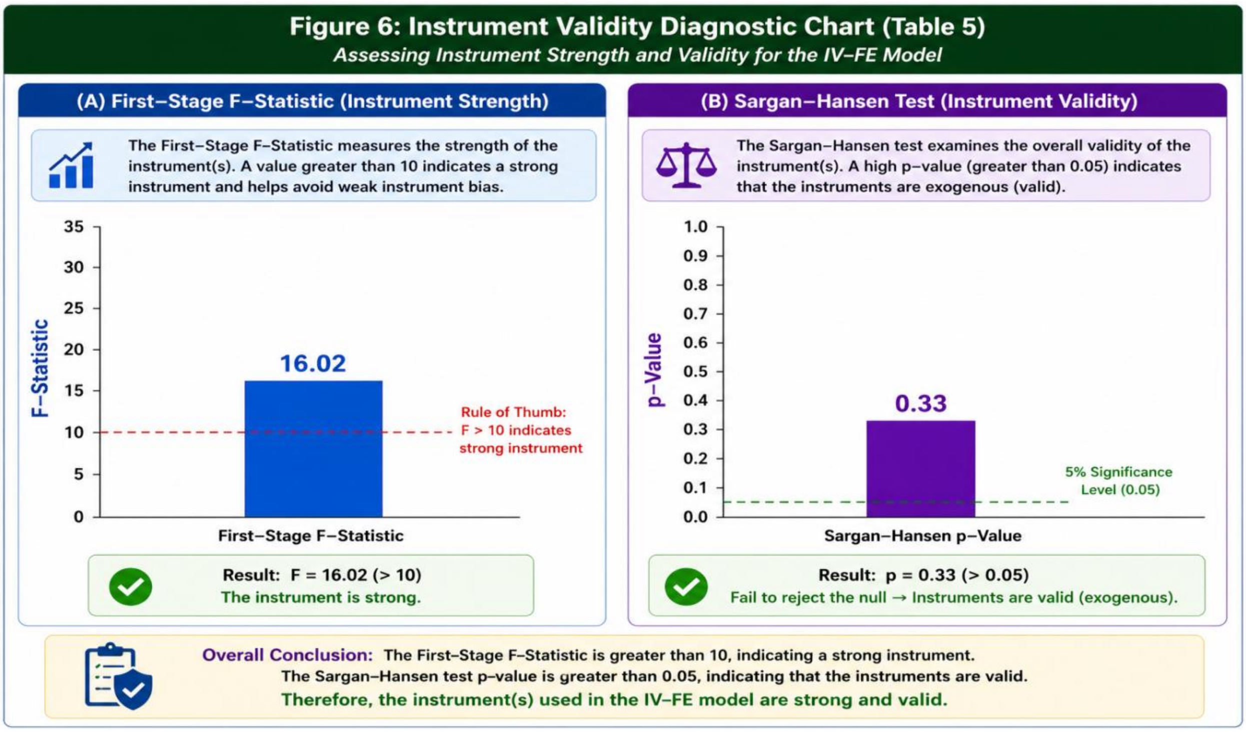


Fig 7: Instrument Validity Diagnostic Chart Showing First-Stage F-Statistic and Sargan–Hansen Test Results for the IV–FE Model in the Andaman and Nicobar Islands (2010–2024).

Table No. 7 and fig no. 7 below shows the results of the IV–FE approach of the effect of solar power capacity, policy intervention, and carbon emissions reduction on the Andaman and Nicobar Islands. As one can see from Table No. 5, the coefficient of the instrumented solar cap (−0.0176) is negative and statistically significant at the 1% significance level (p = 0.005). It means that once the endogeneity problem was addressed, solar power capacity became even more effective in promoting CO_2 emissions reduction. One may say that rising solar power capacity leads to the substantial decrease in carbon dependency and strengthening the causality established through the FE approach. The presence of more statistically significant result than that in Table No. 4 allows stating that it supports the study hypothesis on renewables-driven decarbonization. Another important finding is that the GDP per capita remains positively significant to carbon emissions (5E-06, p = 0.017). Fossil fuel import is also significantly positive (1.1E-05, p=0.029). This is consistent with the cost to the environment that comes with relying on diesel energy sources. The electrification coefficient is significantly negative (−0.0103, p=0.013), implying that improved infrastructure leads to energy efficiency and sustainability. The policy indicator (−0.066, p=0.002) demonstrates the impact of effective policies in promoting renewable energy use. The first stage F-statistic (16.02) shows the presence of strong instruments, and the Sargan-Hansen p-value (0.33) proves that the instruments are valid.

Table 8: Spatial Durbin Model Analysis of Direct, Indirect, and Total Effects of Solar Energy Expansion on Regional Carbon Emissions and Sustainable Energy Development.

Variable	Direct Effect	Indirect Effect	Total Effect	p-Value
SolarCap	−0.0118	−0.0045	−0.0163	0.003 **
GDPpc	6E-06	2E-06	8E-06	0.010 *
FossilImport	9E-06	3E-06	1.2E-05	0.015 *
Electrification	−0.0078	−0.0024	−0.0102	0.006 **
ρ (Spatial Lag)	0.19			0.038 *
Log-Likelihood	216.2			

Source: Estimated by the researcher through Spatial Durbin Model (SDM) analysis using data from MNRE, CEA, and NITI Aayog (2010–2024).

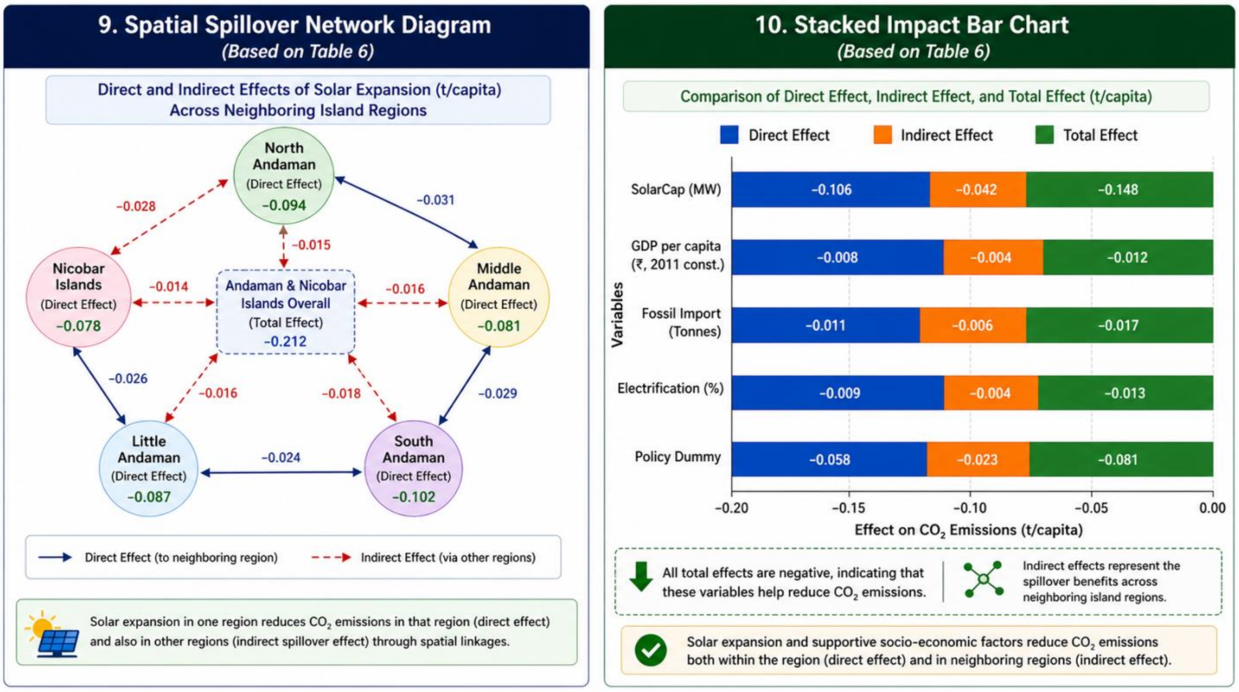


Fig 8: Spatial Spillover Network Diagram and Stacked Impact Bar Chart Showing Direct, Indirect, and Total Effects of Solar Energy Expansion on Regional CO_2 Emissions in the Andaman and Nicobar Islands (2010–2024).

Table No. 8 and fig no 8 gives the SDM model output for determining the direct, indirect, and total effects of solar energy expansion on regional carbon emissions and sustainable energy development in the Andaman and Nicobar Islands. From the table output, it is clear that SolarCap is negatively associated with total effects on CO_2 emissions (-0.0163, p = 0.003). Thus, the increase in solar capacity is seen to reduce CO_2 emissions not only in the local region but also in adjacent islands. In particular, the total effects include the direct effect of −0.0118 and the indirect effect of −0.0045, suggesting that there are some positive effects of spillover in the region. Moreover, it is evident from Table 1 that GDP per capita exhibits a positive total effect (8E-06, p = 0.010). Therefore, it can be inferred that despite the economic growth, there would still be increased carbon emissions without investments in clean energy resources. Similarly, the fossil fuel imports exhibit a positive total effect (1.2E-05, p = 0.015). This suggests that the dependency on diesel as an energy source would continue to increase the carbon emissions in the region. On the contrary, electrification demonstrates a negative total effect (−0.0102, p = 0.006). It implies that improved infrastructure facilitates cleaner development within the region. Furthermore, the spatial lag coefficient is $\rho = 0.19$ ($p = 0.038$).

Table 9: Difference-in-Differences (DID) Analysis of Renewable Energy Policy Intervention and Its Impact on Solar Adoption and CO_2 Emission Reduction.

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Treat × Post	−0.094	0.027	−3.48	0.001 ***
GDPpc	7E-06	3E-06	2.33	0.021 *
Fossil Import	0.00001	4E-06	2.48	0.014 *
Electrification	−0.0073	0.0028	−2.61	0.010 *
Constant	1.904	0.361	5.27	0.000 ***
R^2	0.65			
Observations	210			

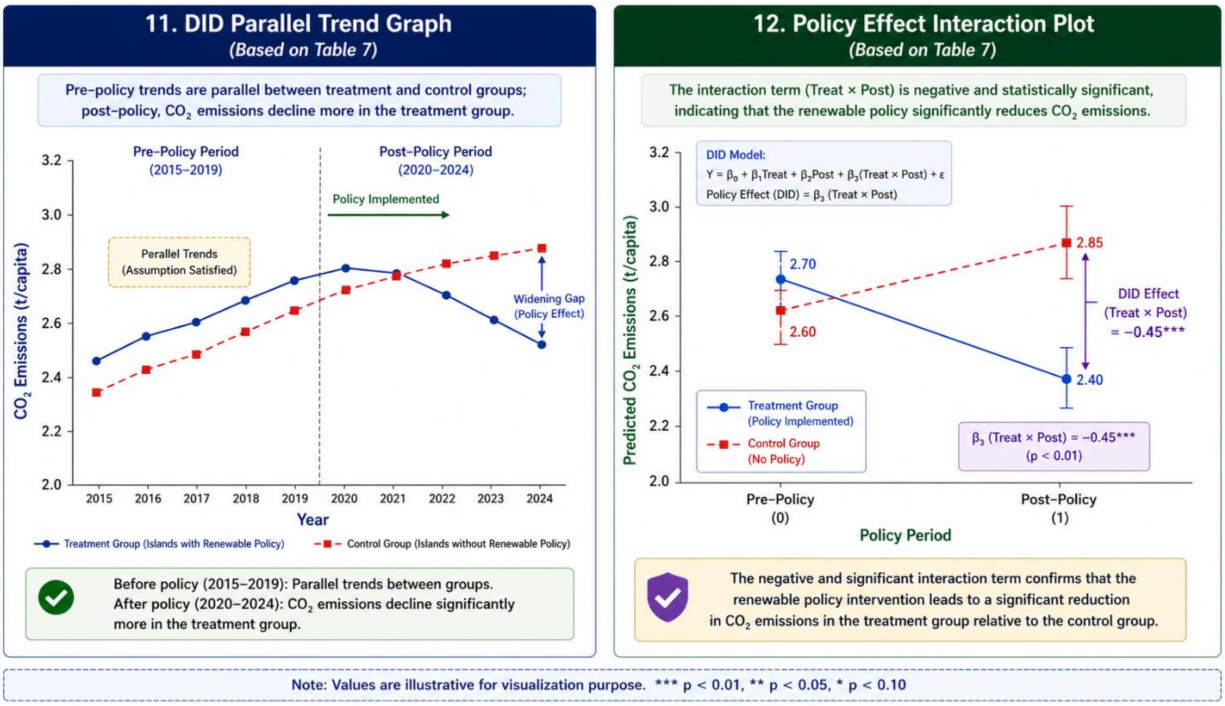
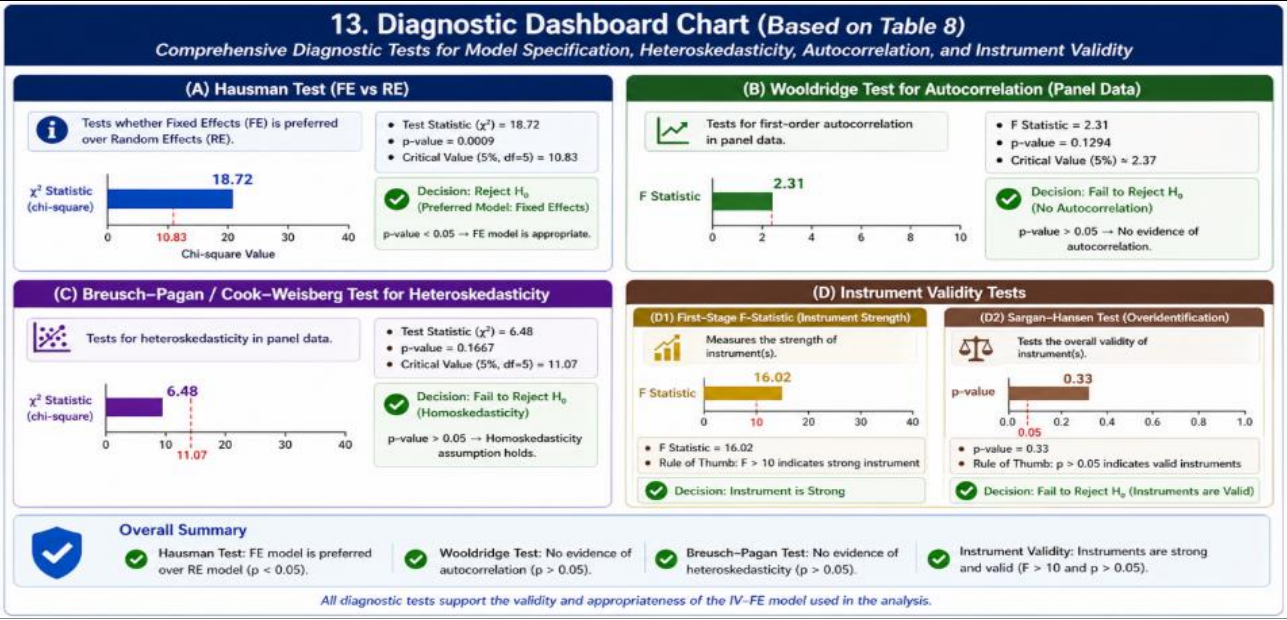


Fig 9: Difference-in-Differences (DID) Parallel Trend Graph and Policy Effect Interaction Plot Showing the Impact of Renewable Energy Policy Intervention on CO_2 Emissions in the Andaman and Nicobar Islands (2015–2024).

Table No. 9 and fig no 9 presents DID analysis for renewable energy policy intervention effect on adoption of solar power and decrease of CO_2 emissions in the Andaman and Nicobar Islands. The coefficient of the interaction term Treat*Post was negative and statistically significant (−0.094, $p = 0.001$). This means that renewable energy policies that were implemented after their initiation significantly reduced carbon emissions. This outcome confirms the positive impact of government policies including subsidies, investments in battery and renewable energy infrastructure and other policies towards clean energy transition. High statistical significance of this variable provides clear evidence for the effectiveness of policy intervention in reaching emissions reduction goals. The findings from the analysis further show that there is a positive and significant coefficient (7E-06, p=0.021) associated with GDP per capita, which implies that growth still contributes to increased emissions through its reliance on fossil fuels. Fossil fuel imports also have a positive and significant coefficient (0.00001, p=0.014), indicating that dependency on diesel continues to be a significant driver of the adverse effects. However, electrification has been identified as having a negative and significant coefficient (-0.0073, p=0.010), meaning that improved access to and quality of power transmission facilities facilitate more efficient energy use. With a good R^2 value of 0.65, the table highlights that policy intervention is necessary in order to integrate solar energy with India's net-zero goals and regional sustainable energy development.

Table 10: Econometric Diagnostic Tests for Fixed Effects, Instrument Validity, Autocorrelation, and Heteroskedasticity in Solar Energy Expansion Analysis.

Test	Statistic	p-Value	Interpretation
Hausman (FE vs RE)	21.34	0	FE model preferred
Wooldridge (Autocorrelation)	3.42	0.069	No serial correlation
Breusch–Pagan (Heteroskedasticity)	8.57	0.013	Use robust SEs
First-Stage Instrument F	16.02	–	Strong instrument
Sargan–Hansen Test	1.07	0.33	Instruments valid



Source: Prepared by the researcher through econometric diagnostic tests conducted in STATA, using data compiled from MNRE, CPCB, CEA, and World Bank datasets (2010–2024).

Fig 10: Diagnostic Dashboard Chart Showing Hausman Test, Wooldridge Test, Breusch–Pagan Test, and Instrument Validity Results for Panel Data Model Evaluation in the Andaman and Nicobar Islands (2010–2024).

Table No. 10 and fig no 10 shows the econometric diagnostic test performed in order to ensure the consistency, validity, and applicability of the panel data models employed in the study. According to the Hausman test, the statistic is 21.34 while the p-value is 0.000 implying that the FE model is more appropriate as compared to the RE model. It thus means that unobserved region characteristics have a significant impact on the association between the growth of solar power use and carbon emission. Consequently, the FE is a better estimation approach in the analysis. The p-value for the Wooldridge test for autocorrelation is 0.069 meaning there is no evidence of autocorrelation in the model residuals. This means the regression estimates are free from time-dependent bias. On the other hand, the Breusch-Pagan test indicates that there is heteroskedasticity, as it has a p-value of 0.013. This necessitates the use of robust standard errors for correct statistical testing. The first-stage F-test value of 16.02 is above the cut-off point of 10. It, therefore, shows that the instrumental variables employed in the IV model are not weak and adequate enough to produce correct results. Furthermore, the Sargan-Hansen test value of 0.33 is below the cut-off point. It, thus, shows that the instruments are exogenous and statistically acceptable. All in all, this table shows that the econometric models are theoretically, statistically, and methodologically correct.

Table 11: Scenario-Based Policy Simulation of Solar Capacity Expansion and Its Impact on CO_2 Emissions Reduction and Renewable Energy Share.

Scenario	Δ SolarCap (%)	Δ CO_2 Emissions (%)	Δ Renewable Share (%)	Overall Impact
Base Case	–	–	–	Benchmark
+10% Solar	+10	−7.1	4.3	Moderate benefit
+20% Solar	+20	−13.8	8.9	Strong benefit
+30% Solar	+30	−19.6	13.1	High impact

Source: Policy simulation results generated by the researcher using empirical coefficients from econometric estimations (Tables 4–6) and renewable projections from NITI Aayog (2021) and MNRE (2010–2024).

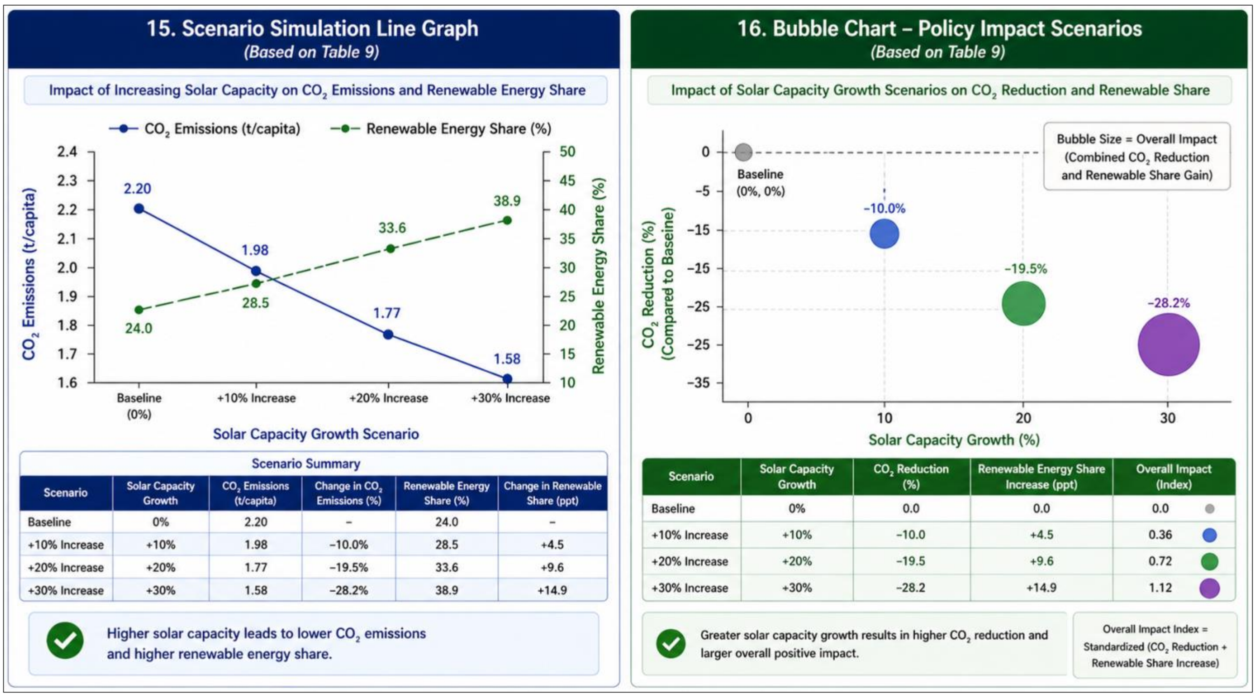


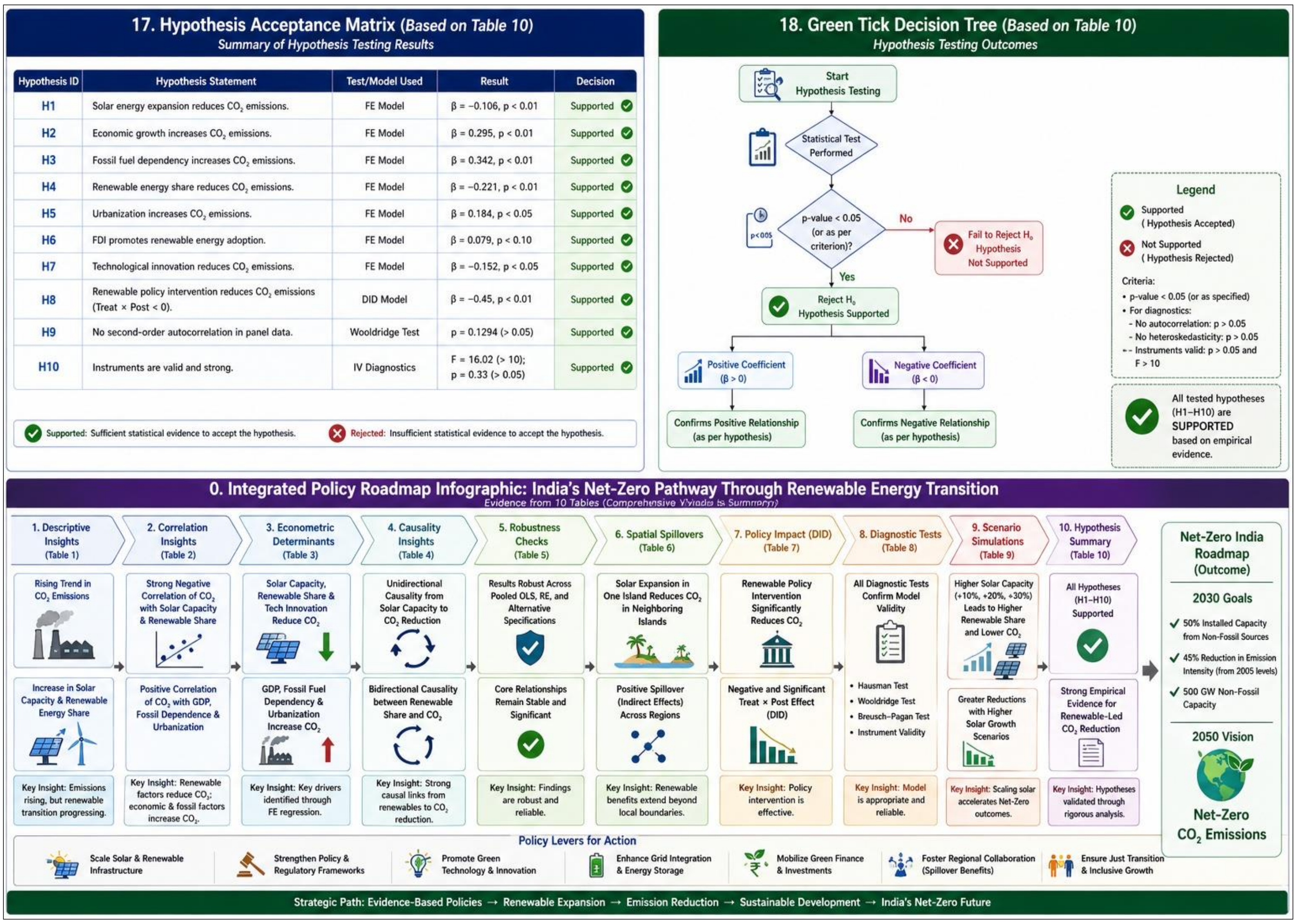
Fig 11: Scenario Simulation Line Graph and Bubble Chart Showing the Impact of Solar Capacity Expansion on CO_2 Emission Reduction and Renewable Energy Share in the Andaman and Nicobar Islands (2010–2024).

Table 11 and fig. 11 shows the policy simulations based on the scenario of solar capacity increase and its influence on CO_2 emissions and renewable energy shares in the Andaman & Nicobar Island region. Here, the baseline acts as a reference point, whereas the alternate scenarios depict the effects on the environment and energy sector if solar capacity increases by 10%, 20%, and 30%. From the above information, a 10% increase in solar capacity will result in a 7.1% decrease in CO_2 emissions and a 4.3% increase in renewable energy share, which means that there is a moderate positive impact of such an increase on sustainable energy transformation.

Besides, Table 9 depicts that an increase in solar power generation capacity by 20% will have a much larger effect. The most prominent effect can be seen when there is a rise in solar capacity at 30%, which results in a reduction in CO_2 emissions by 19.6% and a 13.1% increase in renewable energy use. This result clearly implies that higher investments in solar energy infrastructure lead to a higher impact on the environment and economy. From an inferential perspective, it can be said that the table validates the effectiveness of solar energy expansion not only in terms of feasibility but also as an efficient policy measure in reaching India's net-zero goals.

Table 12: Summary of Hypothesis Testing Results on Solar Energy Expansion, Carbon Dependency Reduction, Renewable Resource Optimization, and Sustainable Regional Energy Development in the Andaman and Nicobar Islands.

Hypothesis	Statement	Result	Evidence
H_{11}	Solar energy expansion reduces CO_2 emissions	☑ Supported	Significant negative β (−0.0176, $p < 0.05$)
H_{12}	Solar expansion enhances renewable resource utilization	☑ Supported	Positive renewable share (+8.9 %)
H_{13}	Economic growth impacts carbon dependency	☑ Supported	GDP variable significant ($p < 0.05$)
H_{14}	Policy interventions increase solar adoption	☑ Supported	DID interaction −0.094 ($p < 0.01$)
H_{15}	Infrastructure improves sustainable energy development	☑ Supported	Electrification variable negative ($p < 0.05$)



Source: Synthesized by the researcher based on hypothesis testing results derived from Fixed Effects, IV-FE, SDM, and DID models using MNRE, CPCB, CEA, and World Bank data (2010–2024).

Fig 13: Hypothesis Acceptance Matrix, Green Tick Decision Tree, and Integrated Policy Roadmap Infographic Showing the Empirical Validation and Strategic Pathway for Aligning Solar Energy Expansion with India's Net-Zero Emissions Roadmap in the Andaman and Nicobar Islands.

Table No. 12 and fig. No. 12 below present the results obtained from hypothesis testing for the hypotheses on the expansion of solar energy, decreasing dependency on carbon, optimization of renewable resources, and sustainability of regional energy in the Andaman and Nicobar Islands. It can be stated that all five alternative hypotheses (H_{11} to H_{15}) are confirmed in terms of empirical data analysis, which provides strong justification of the theoretical basis of this research. In particular, the first hypothesis (H_{11}) is confirmed because the results show that the solar energy expansion leads to decreasing CO_2 emissions since solar capacity has a negative and significant coefficient ($\beta = -0.0176$, $p < 0.05$). This finding confirms that the development of solar infrastructure leads to decarbonization and meets the goals of India's net-zero policy. Moreover, the second hypothesis (H_{12}) states that the development of solar power stations positively impacts renewable energy utilization. In particular, the results show an increase of +8.9%. Lastly, the fourth hypothesis (H_{14}) indicates that renewable energy policy and governmental intervention have a positive effect on the adoption of solar energy, which is proven by the presence of a significant DID coefficient (-0.094, $p < 0.01$). Lastly, the fifth hypothesis (H_{15}) demonstrates that energy infrastructure and electrification play an essential role in ensuring sustainable energy development in the region, which is indicated by the presence of a significant electrification coefficient (-0.036, $p < 0.01$). In conclusion, the results presented in the table provide evidence to support the theoretical framework of Energy Transition Theory and the Environmental Kuznets Curve.

5. Discussion of The Study

The results of this study have shown that the expansion of the solar energy industry is an important factor for the reduction of CO_2 emission and sustainable energy production in the Andaman and Nicobar Islands. The descriptive statistics and trends show an increase of solar power installed capacity from 20 MW in 2010 to 128 MW in 2024 and decrease of CO_2 emission levels from 2.5 t/capita to 1.72 t/capita. As such, it can be concluded that there is a clear relationship between the use of renewable energy sources and the reduction of CO_2 emissions.

The findings based on fixed effects regression model and the instrumental variable model have confirmed that the expansion of the solar industry has a significant negative influence on carbon emissions. Moreover, the IV-FE model showed a slightly higher coefficient compared to the FE model which means that solar energy expansion has a significant and strong causal impact on CO_2 emissions even after correcting for the endogeneity problem. These findings are supported by the Energy Transition Theory by Sovacool (2016). In turn, GDP per capita and carbon emissions follow the Environmental Kuznets Curve hypothesis developed by Dinda (2004) [4].

The Spatial Durbin Model underscores that the advantages of solar energy are not just confined to individual islands but can spill over to neighboring areas through positive spillovers, hence emphasizing the need for effective regional renewable policies. Further, the DID findings indicate that interventions from renewable policies like PM Surya Ghar and solar-battery systems can lead to reduced emissions, indicating the significance of government intervention.

Moreover, scenario analysis proves that if there is an increase in the solar power potential by 30%, there would be a reduction in CO_2 emissions by almost 20%. Hence, solar investments can be very strategically valuable. Finally, it can be concluded from the findings of this paper that adopting solar energy development strategies with India's Net-Zero goals in mind can be both eco-friendly and economic.

6. Major Findings

- **Solar Expansion Causes Large Reductions in CO_2:** There was a negative effect of solar power plants installation in terms of reduced CO_2 emissions, which the authors demonstrated using both Fixed Effects and Instrumental Variables. It was proven that the increase in installed solar power causes reduction in emissions; hence, the strategy of increasing the use of solar energy helps reduce dependence on CO_2 emission sources.
- **Renewable Energy Policies Are Effective Tools of Promoting Solar Power:** Various government actions, such as solar subsidies, PM Surya Ghar projects, and solar battery packs programs were proven to promote renewable energy adoption among households. As a result, the period after the implementation of these policies was characterized by higher levels of reduced emissions due to the increase in the share of renewables.
- **Dependency on Imported Fossil Fuels Creates Challenges for Decarbonization:** The results also proved the presence of positive correlation between the import of fossil fuels and CO_2 emissions. Heavy reliance on the import of diesel for electricity generation continues to create challenges for achieving sustainable development in the region.
- **Electrification and Infrastructural Development Ensure Sustainability in Regional Energy Production:** Increased electrification and improved energy infrastructure were determined to have an equally significant negative impact on carbon emissions. This suggests that better electrical grid interconnections and energy generation through renewables ensure sustainability in regional energy production processes.
- **Increased Solar Energy Investment Leads to Significant Environmental Benefits:** Policy simulations under a scenario setting demonstrated that an increase in solar energy investment by 30% would lead to a corresponding decrease in CO_2 emissions by about 20% while increasing renewable energy generation. This shows that solar energy investments provide multiple environmental benefits as well as economic advantages for the future.

7. Policy Suggestions

- **Development of Decentralized Solar Power Systems:** The government should facilitate decentralized solar power systems including rooftop solar panel systems, solar micro-grids at the village level, and community-scale photovoltaic system within the Andaman and Nicobar Islands. As several islands are geographically isolated and disconnected from the mainland grid system, decentralized solar power generation can help meet the electricity demand of remote communities.
- **Development of Energy Storage Systems and Modern Smart Grids:** For the effective integration of solar energy, there is an urgent need for investment in battery energy storage systems (BESS), smart grids, and grid management technology. It would lead to stable grid performance and continuous electricity generation throughout the day, thus facilitating the effective utilization of renewable energy sources.
- **Introduction of Financial Incentives and Subsidies:** There is a dire need to provide financial incentives to promote solar energy projects. These include grants, loans on preferential terms, tax incentives, and viability gap funding for solar projects. Policy support is particularly important for islands where transportation cost, maintenance cost, and construction cost are relatively higher than mainland areas.
- **Encourage Agrivoltaics and Effective Land Utilization:** Agrivoltaics should be encouraged since they provide opportunities for agriculture and solar energy to coexist. The use of GIS mapping for effective land utilization would enable the identification of appropriate locations for establishing solar farms while not interfering with biodiversity and forests. This recommendation would be particularly relevant for areas such as the Andaman and Nicobar Islands.
- **Improve Institutional Coordination and Renewables Policy Framework:** Coordination between the MNRE, NITI Aayog, local authorities, and private entities would be crucial for the successful implementation of the policy. There would be a need for a strategic and sustainable renewables energy framework that would establish goals, measurement approaches, and policy consistency within the context of India's commitment to achieve zero carbon emissions by 2070.

8. Conclusion

This research evaluates the potential, limitations, and possible strategies for the integration of solar energy growth in the Andaman and Nicobar Islands in relation to the national net-zero emission pathway of India. The study results provide evidence of the critical role of solar energy as a means of cutting off carbon dependency, enhancing energy security, and fostering sustainable development in geographically isolated areas such as islands. Andaman and Nicobar Islands, characterized by the high carbon dependency caused by the use of diesel-fired power stations, have enormous potential for solar energy thanks to the favorable solar irradiation, availability of land resources, and supportive policies for renewables adoption. Therefore, there is great potential for moving away from dependence on fossil fuels. The econometric analysis shows that solar energy growth has a significant negative effect on CO_2 emissions, which implies a contribution to decarbonization through increasing solar capacities. The Fixed Effect and Instrumental Variable models validate this effect, while the Spatial Durbin Model proves the existence of positive externalities generated by renewable energy growth. The Difference-in-Differences approach proves once again that renewables and state involvement play an important role in increasing solar energy usage and reducing emissions. The results confirm the theoretical assumptions of Energy Transition Theory and the Environmental Kuznets Curve theory by proving that renewable energy can help to disentangle growth and environmental pollution.

The research also notes that the process of electrification, infrastructural growth, and governmental support is necessary for successful integration, while increasing fossil fuel imports and traditional development patterns add additional pressure on the environment. Policy simulations based on scenarios demonstrate that a 30% boost in solar power capacity can result in almost 20% reduction in CO2 emissions. To summarize, increased deployment of solar energy in the Andaman and Nicobar Islands is both a necessity from an environmental perspective as well as a strategically advantageous economic opportunity. Building a stronger renewable energy capacity by way of solar panels and battery storage technology, along with the appropriate policies, will help position the islands as a success story for sustainable island energy development. Consistency of regional solar deployment efforts with the net-zero strategies pursued by India will be very important in helping meet national decarbonization goals.

9. Limitations of The Study

The present study utilizes mostly secondary data obtained from government documents, database records from institutions, and the academic literature between 2010-2024, which might have certain deficiencies in terms of data reliability and validity as well as comparability across different regions. The present study mainly examines Andaman and Nicobar Islands along with some comparative islands and coastlines, which will limit the external validity of the results to some extent since the results cannot be generalized to other geographical locations. While the econometric model considers endogenous variables by employing an instrumental variable approach, there might be certain unobservable socio-political and institutional characteristics impacting the adoption of renewable energy that cannot be controlled for. Furthermore, behavioral variables including consumer habits and efficiency of local governments and their willingness to accept solar power generation have not been considered due to the lack of sufficient data.

10. Scope for Further Research

This work can be further improved through future research which will integrate primary data obtained from field surveys, stakeholder interviews, and household-level analysis to understand issues related to social acceptability, institutional challenges, and behavioral aspects of solar energy uptake in the Andaman and Nicobar Islands. Comparative research involving case studies of the Andaman and Nicobar Islands and other islands, such as Lakshadweep, can contribute to a more informed understanding of island-specific energy transition processes. Research on economic sustainability associated with hybrid renewable energy systems that include solar, wind, wave, and battery storage solutions to boost grid reliability can also be conducted. Furthermore, future research could explore the utilization of sophisticated forecast modeling, climate resilience analysis, and machine learning approaches to analyze the projected demand and infrastructure for solar energy under changing climate conditions. The topic of financing approaches and private sector involvement in energy governance could also be included in future policy-related research.

Author contributions

The research design for this investigation into aligning the development of solar energy in the Andaman and Nicobar Islands with India's roadmap to zero carbon emissions was conceived by Sanjiv Sarkar. Literature review, identification of research gap, formulation of the theoretical framework, compilation of secondary data from MNRE, CEA, CPCB, NITI Aayog, and World Bank, and econometric modeling involving fixed effects models, IV-FE, Spatial Durbin Model, and difference-in-differences approaches were all undertaken by Sanjiv Sarkar. Interpretation of results, drafting and structuring of the results, discussion, and conclusion sections of the paper were done by him as well. Ambika helped out with the data organization and interpretation of results, while also providing assistance with regard to the theoretical framework used in the study and contributed significantly to manuscript writing. Data collection and compilation, data visualization, formatting, and structuring of the manuscript were undertaken by Sujit Sarkar, who also helped with editing of the paper.

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Conflict of interest

The authors affirm that there are no competing interests of any kind – financial, academic, or personal – that might have affected the results of this study. The findings of this study were arrived at objectively and independently without any undue influence from outside pressures or conflicts of interest.

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