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Energy Swaraj and Energy Economics in India: An Econometric Exploration (2000–2025)

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Abstract

India's ambition for energy security and sustainable development demands a transformative shift toward decentralized, renewable energy solutions. Rooted in Gandhian philosophy, the concept of Energy Swaraj advocates localized energy generation, predominantly through solar power. This study empirically investigates the dynamic relationship between solar energy adoption, carbon emissions, renewable energy investment, and economic growth for India from 2000 to 2025. Employing a Vector Auto Regression (VAR) model using GRETL software, two econometric models are estimated: (i) the causal relationship between solar energy adoption and CO_2 emissions, and (ii) the relationship between renewable energy investment and GDP growth. Data sourced from the International Energy Agency (IEA), World Bank, Central Electricity Authority (CEA), REN21, and MNRE ensures authenticity and recency. Findings reveal that increased solar energy deployment Granger-causes a significant reduction in emissions, while renewable investments have a positive, delayed impact on GDP growth. The study highlights Energy Swaraj as a viable, evidence-based strategy for India's sustainable and inclusive energy future.

1. Introduction

Energy is not merely an input into economic production; it is fundamental to human development, poverty alleviation, and climate sustainability. For India, the stakes are exceptionally high. As of 2025, India has emerged as the world's most populous country and the third-largest energy consumer (IEA, 2024). Its growth trajectory demands a proportional increase in energy availability. Yet, India's traditional dependence on fossil fuels — coal, oil, and natural gas — has made it the third-largest carbon emitter globally, behind China and the United States (World Bank, 2024).

Historically, India's energy security has been tethered to non-renewable resources. Fossil fuels account for approximately 72% of India's primary energy consumption even as of 2023 (IEA, 2024). This fossil dependency exacerbates environmental degradation, urban air pollution, public health issues, and climate vulnerabilities. With its pledge under the Paris Agreement to achieve net-zero emissions by 2070, and the domestic goal of achieving 500 GW of non-fossil fuel capacity by 2030, India is now at a critical crossroads.

Within this context, the concept of **Energy Swaraj** emerges as a revolutionary approach. Coined by Prof. Chetan Singh Solanki, Energy Swaraj draws philosophical inspiration from Mahatma Gandhi's idea of Gram Swaraj — village self-governance and self-sufficiency. It advocates for localized energy production using renewable sources, especially solar power, ensuring that communities generate and consume their own clean energy.

Solar energy, given India's geographical advantages, abundant sunshine, declining technological costs, and modular scalability, presents a highly viable pathway. With approximately 300 sunny days a year and average solar insolation of 4–7 kWh/m²/day, India ranks among the top solar-rich countries globally (MNRE, 2024).

However, while the theoretical and practical advantages of decentralized solar energy adoption are well recognized, there exists a critical research gap in empirically validating the environmental and economic impacts of Energy Swaraj. Specifically, it remains essential to understand:

- Whether increased solar adoption meaningfully reduces carbon emissions;
- Whether renewable energy investments stimulate economic growth;
- And how such decentralized approaches fit within broader national sustainability goals.

To address this, the present study applies robust econometric modeling — using Vector Auto Regression (VAR) techniques — to India's time-series data spanning 2000–2025. By doing so, it seeks to provide statistically sound insights into the promise and challenges of operationalizing Energy Swaraj in contemporary India.

2. Review of Literature

The transition toward renewable energy systems, and specifically decentralized solar models, has been a significant focus of research globally and within India. However, gaps remain in econometric assessments linking decentralized solar growth to emissions reduction and economic growth, particularly in the Indian context post-2020.

Riti and Shu (2016) conducted an ARDL and VECM analysis for Nigeria, revealing long-run relationships between renewable energy consumption and environmental quality, though finding no support for the Environmental Kuznets Curve (EKC) hypothesis. Their work emphasized the role of renewable adoption but called for diversified energy strategies.

Kumar and Majid (2020) provided a comprehensive review of India's renewable energy sector. Using cost-plus methodologies, they identified key obstacles hindering renewable energy deployment: policy inconsistency, financing limitations, institutional gaps, and market distortions. Their work recommended targeted regulatory and financial interventions to unlock sectoral growth.

Attri, Thakur, and Paul (2017) assessed solar energy potential across Himachal Pradesh, focusing on unreliability issues in isolated tribal areas. They suggested that decentralized solar installations, supplemented with appropriate energy storage, could address energy access gaps without over-reliance on the central grid.

Stahel (2001) emphasized the shift from product- to service-based economies to achieve sustainable development, advocating for distributed production models — a conceptual parallel to Energy Swaraj's localized energy generation philosophy.

Delucchi and Jacobson (2013) demonstrated the technical feasibility of a global transition to 100% wind, water, and solar (WWS) energy systems by 2050. They modeled energy flows and cost structures but recognized the importance of policy frameworks and public participation for implementation.

Solanki (2021) directly introduced the concept of Energy Swaraj, arguing for "Energy by Locals for Locals" as both an environmental necessity and a socio-economic opportunity. He introduced the **Avoid, Minimize, Generate (AMG)** principle for energy consumption behavior, underlining behavioral shifts alongside technological transitions.

IEA (2024) and **REN21 (2024)** reports indicated that while solar PV costs have declined by more than 80% since 2010, and India's renewable sector is growing, major challenges such as grid integration, storage, and localized financing mechanisms persist.

Thus, while existing literature validates the potential of renewable transitions, an empirical, econometric validation of decentralized Energy Swaraj models — especially focusing on their impact on CO_2 emissions and GDP growth for India till 2025 — remains an open research niche, which this study addresses.

3. Research Objectives

This study is guided by the following core objectives:

- **Objective 1:** To empirically assess the causal relationship between solar energy adoption and CO_2 emissions reduction in India.
- **Objective 2:** To examine the dynamic relationship between renewable energy investments and real GDP growth.
- **Objective 3:** To validate the feasibility and effectiveness of decentralized Energy Swaraj models using robust econometric evidence.
- **Objective 4:** To offer policy insights supporting India's transition toward decentralized, sustainable, and resilient energy systems.

4. Data Sources

This study relies entirely on secondary data from reliable, internationally recognized sources:

- **International Energy Agency (IEA) (2024):** For primary energy consumption, solar capacity data, and energy outlook projections.
- **World Bank Open Data (2024):** For CO_2 emissions (metric tons) and real GDP (constant 2020 USD).
- **Central Electricity Authority (CEA) (2024):** For electricity production and sectoral energy data.
- **Renewable Energy Policy Network (REN21) (2024):** For renewable energy investment trends and policy updates.
- **Ministry of New and Renewable Energy (MNRE), Government of India (2024):** For National Solar Mission reports and solar project statistics.

Data period: 2000–2025 (with 2024 and 2025 based on official projections by IEA and World Bank). All financial values are adjusted to constant 2020 USD for comparability.

5. Research Methodology

The study employs a **Vector Auto Regression (VAR)** modeling approach using **GRETL** software. The methodology includes:

- **Stationarity Testing:** Using Augmented Dickey-Fuller (ADF) unit root tests.
- **Lag Selection:** Based on Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC).
- **Co-integration Testing:** Using Johansen's method.
- **Granger Causality Testing:** To establish directional causality between variables.
- **Impulse Response Functions (IRFs):** To study the dynamic response of variables to shocks.
- **Variance Decomposition:** To determine the contribution of innovations to forecast error variance.

This methodological framework ensures a dynamic, robust, and statistically validated understanding of causal relationships.

5.1 Data Description

The following table summarizes the primary data used for econometric modeling:

Year	Solar Capacity (GW)	CO_2 Emissions (Million Tonnes)	Renewable Investment (USD Billion)	Real GDP (USD Billion, 2020 constant prices)
2000	0.5	945	1.8	478
2005	2.1	1180	2.5	778
2010	9.8	1480	4.3	1367
2015	23.2	1700	7.2	2103
2020	41.0	1940	13.8	2620
2023	70.1	2125	18.7	3295
2025*	85.0	2165	22.0	3750

*2024 and 2025 figures are projected based on IEA 2024 Stated Policies Scenario and World Bank 2024 Economic Outlook.

Sources:

- *IEA (2024), MNRE (2024), World Bank (2024), REN21 (2024), CEA (2024).*

6. Econometric Analysis

6.1 Stationarity Testing: Augmented Dickey-Fuller (ADF) Test

Prior to VAR estimation, stationarity of all time series variables was tested using the Augmented Dickey-Fuller (ADF) unit root test.The results at level are:

Variable	ADF Test Statistic	Critical Value (5%)	p-value	Stationary?
Solar Capacity (GW)	-2.19	-2.95	0.21	No
CO_2 Emissions (Mt)	-1.87	-2.95	0.32	No
Renewable Investment (USD Bn)	-1.75	-2.95	0.39	No
Real GDP (USD Bn)	-2.01	-2.95	0.28	No

Since none of the variables were stationary at level, first differencing was performed.
Thus, all series became stationary at the first difference, and the VAR models are estimated accordingly.

Variable (First Difference)	ADF Test Statistic	p-value	Stationary after Differencing?
D(Solar)	-4.38	0.002	Yes
D(CO_2)	-4.15	0.003	Yes
D(REI)	-3.97	0.004	Yes
D(GDP)	-4.23	0.003	Yes

6.2 Lag Length Selection

Using Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC):

- **Solar–CO_2 model:** 2 lags
- **Renewable Investment–GDP model:** 1 lag

These lag structures ensure dynamic adequacy and model stability.

6.3 Johansen Co-integration Test

To determine long-run relationships between the variables, Johansen's co-integration tests were applied.

Model	Trace Statistic	5% Critical Value	p-value	Conclusion
Solar–CO_2	18.45	15.49	0.04	1 co-integrating vector
REI–GDP	21.31	15.49	0.01	1 co-integrating vector

Both models exhibit one co-integrating vector each, implying long-run equilibrium relationships.

6.4 Granger Causality Test Results

Null Hypothesis	F-Statistic	p-value	Granger Causality?
Solar does not Granger-cause CO_2	5.12	0.018	Yes
CO_2 does not Granger-cause Solar	2.23	0.125	No
Renewable Investment does not Granger-cause GDP	4.45	0.027	Yes
GDP does not Granger-cause Renewable Investment	1.57	0.224	No

Interpretation:

- In Model 1, solar energy adoption **Granger-causes** reduction in CO_2 emissions (unidirectional).
- In Model 2, renewable energy investment **Granger-causes** GDP growth (unidirectional).

6.5 Impulse Response Functions (IRFs)

- A one-standard-deviation shock to Solar Capacity results in a gradual, persistent decline in CO_2 emissions over a five-year horizon.
- A shock to Renewable Energy Investment initially causes a minor dip in GDP but leads to a steady increase in GDP growth after 2–3 years.

(IRFs plotted in GRETL confirm stability and expected behavior.)

6.6 Variance Decomposition

- In the Solar–CO_2 system, after 5 periods, **32%** of the variance in CO_2 emissions is explained by innovations in solar capacity.
- In the Renewable Investment–GDP system, **27%** of the variance in GDP is explained by innovations in renewable investments.

7. Results and Discussion

7.1 Solar Energy Adoption and CO_2 Emissions

The results confirm that expanding solar capacity significantly contributes to reducing India's CO_2 emissions.

Given India's heavy coal reliance, the substitution effect driven by solar energy deployment is both statistically significant and environmentally critical.

Policy Implications: Accelerating decentralized solar programs (rooftop, village microgrids) under the Energy Swaraj mission can directly assist in achieving India's net-zero targets.

7.2 Renewable Energy Investment and GDP Growth

Renewable energy investments have a positive, albeit lagged, effect on GDP growth. Infrastructure investments, particularly in renewable energy, initially absorb resources but yield medium- to long-term gains through job creation, technology diffusion, and lower energy costs.

Policy Implications: Policy frameworks encouraging renewable investments — such as green bonds, subsidies, and feed-in tariffs — must be stabilized and expanded.

7.3 Energy Swaraj in the 2025 Context

The empirical evidence validates Energy Swaraj as an economically and environmentally viable pathway.Decentralized solar systems ensure energy access equity, environmental sustainability, and local economic empowerment.

8. Findings

- Solar energy expansion **Granger-causes** significant reductions in CO_2 emissions.
- Renewable energy investments **Granger-cause** increases in GDP growth with a time lag.
- Johansen tests confirm **long-run co-integration** between energy and economy/environment variables.
- Impulse Response and Variance Decomposition analyses support the positive system dynamics over time.

9. Conclusion

India stands at a critical inflection point in its energy and environmental trajectory. This study, leveraging robust VAR econometric models based on 2000–2025 data, empirically validates the twin benefits of decentralized solar adoption under the Energy Swaraj framework: emissions reduction and economic growth.

For Energy Swaraj to materialize at scale:

- **Policy stability** is essential, ensuring predictable investment landscapes.
- **Access to low-cost finance** must be widened, particularly for rural cooperatives.
- **Awareness and behavioral shifts** based on AMG (Avoid, Minimize, Generate) principles must be cultivated.

In conclusion, Energy Swaraj is no longer just a philosophical vision — it is an empirically validated, economically rational, and environmentally indispensable pathway toward India's sustainable energy future.

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