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Energy Dynamics in Indian Agriculture: Consumption Trends and Economic Impacts

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ABSTRACT

Energy plays a pivotal role in driving modern agricultural growth and technological advancements, particularly in India, where agriculture continues to be a fundamental pillar of the economy. During the fiscal year 2022–23, electricity consumption in the agricultural sector reached 240.80 TWh, accounting for 17.52% of the nation's total electricity use. This study examines trends in agricultural electricity consumption and investigates its linkages with agricultural growth. The analysis of energy efficiency in agriculture is based on data pertaining to gross sown area, irrigated area, and total agricultural production for the period 1982–83 to 2022–23. Additionally, the relationship between electricity consumption and agricultural GDP is explored using secondary data on electricity usage in agriculture and GDP from 1990–91 to 2022–23, encompassing major states across India. The findings highlight a substantial increase in agricultural electricity consumption, which rose from 17,817 GWh in 1982–83 to 240,800 GWh in 2022–23, with a compound annual growth rate (CAGR) of 6%. Electricity consumption per unit of cropped area also exhibited an upward trend, with a CAGR of 5.6%. Results from panel fully modified ordinary least squares (FMOLS) analysis revealed a positive and statistically significant relationship between electricity consumption and agricultural GDP, indicating that a 1% increase in electricity use leads to a 0.24% rise in real GDP. Furthermore, both long-run and short-run causality tests confirm that electricity consumption is a key determinant of agricultural GDP growth, emphasizing its crucial role in the sector's development. The paper also emphasizes the significant impact of agricultural power subsidies on groundwater exploitation, highlighting the importance of implementing effective rationing policies to regulate electricity usage more efficiently than relying solely on tariff adjustments. The findings call for strategies aimed at enhancing energy use efficiency in agriculture to accomplish resource conservation and equitable development.

Keywords Agricultural growth, Electricity consumption, Electricity use efficiency, Panel cointegration, Regression model.

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INTRODUCTION

Agriculture occupies a significant position in India's economy, providing livelihood and employment to over 54% of the population and contributing around 14% to the Gross Domestic Product (GDP) (PIB 2023). As the foundation of the country's economy, the sector has profound implications for the overall demand and supply of energy. With the global population projected to reach 9.7 billion by 2050, the United Nations estimates that food production must increase by 70% to meet the growing demand (FAO 2018). Achieving this target within the constraints of limited energy and water resources is among the most important challenges of the 21st century (Scott and Sharma 2009).

Energy is a fundamental resource in any economy, and there is a strong link between energy use and economic growth. In India, this connection is evident in the agriculture sector, where energy is crucial for various activities, including land preparation and irrigation (Kabbur *et al.* 2020). Over the years, the sector's energy consumption has shifted dramatically from relying on human and animal power to electricity and carbon-based fuels. This transition reflects the broader trend of increased mechanization in Indian agriculture, supported by government policies and private-sector initiatives (Shahbaz *et al.* 2011). For example, the sale of tractors and agricultural machinery has surged, contributing to a rise in high-speed diesel (HSD) consumption, making agriculture a significant consumer of diesel in the country (Destek and Sarkodie 2019)

However, in recent years, there has been a notable shift towards greater reliance on electricity as the primary energy source in agriculture, replacing carbon-based fuels like diesel (Jha 2013). Electricity consumption in Indian agriculture has seen a consistent increase, with the sector consuming 240.8 TWh in 2022-23, accounting for approximately 17.15% of the country's total electricity consumption (Energy Statistics 2023). This trend has been driven by various factors, including government policies that provide free or subsidized electricity to farmers (Narayanamoorthy *et al.* 2018). While these policies have supported agricultural productivity, additionally, they have resulted in the dominance of groundwater as the primary irrigation source and imposed financial burdens on the government and power companies (Gulati and Pahuja 2015).

The relationship between electricity consumption and agricultural growth is complex and multi-faceted (Kumar *et al.* 2022). Increased access to electricity has facilitated more extensive and efficient irrigation practices, boosting agricultural productivity (Birner *et al.* 2011). However, the reliance on free and limitless electricity has an impact on sustainability because it promotes excessive groundwater extraction (Vatta *et al.* 2022).

The past and current patterns of energy generation and consumption will play a decisive role in shaping India's economic future and the well-being of the population. Significant increases across various sectors have marked the growth of electricity consumption in India (Jha *et al.* 2012). The manufacturing sector includes consistently accounted for the largest portion, consuming 595 TWh, or 42.39% of the total electricity consumption. Meanwhile, the agriculture and forestry sectors have also seen substantial growth in electricity usage (Mukherji 2007). The use of electricity in agriculture in particular, has surged from 17,817 GWh in 1982-83 to 240,800 GWh in 2022-23, reflecting a rate of compound annual growth (CAGR) of 6% over this period. This notable increase underscores the growing importance of electricity in agriculture, as the sector's energy use is directly tied to food security and rural livelihoods (Mukherji 2022). Despite the dominance of the industrial sector, it is impossible to ignore the importance of using electricity in agricultural activity, given its critical role in sustaining the nation's agricultural productivity and supporting the rural economy (Badiani and Jessoe 2018).

In light of these factors, this study aims to investigate the causality and over time association between the real gross domestic product of agriculture and related sectors and the amount of electricity used for agricultural purposes in the major Indian states between 1993 and 2023. In this context, the study aims to achieve the following specific objectives:

(1) To study the trends in usage of electricity in Indian agriculture.

(2) To evaluate the relationship between electricity use and the development of agriculture.

(3) To analyze the impact of agricultural electricity subsidy on groundwater extraction.

By addressing these objectives, this study attempts to give an in-depth overview of the role of electricity in Indian agriculture, offering insights into how energy policies and practices can be optimized to support sustainable agricultural development.

MATERIALS AND METHODS

The study is based on secondary data compiled from various sources. The dataset covers country's main states. Data on usage of energy in agriculture was collected the Central Electricity Authority, Annual Report 2023, GOI, Ministry of Power (CEA 2023a). Data on total cropped area (CA) and total irrigated area (IA) are from the Land Use Statistics at a Glance 2022, and total agricultural production is from Agricultural Statistics at a Glance 2022 published by the Directorate of Economics & Statistics, Government of India. Further, data on Gross Domestic Product (GDP) was sourced from the Ministry of Statistics and Program Implementation, Government of India (Directorate of Economics and Statistics, 2022 and 2023).

Patterns of electricity use in agriculture

Electricity is the dominant energy source for groundwater extraction in India. This study first examines the trends in use of electrical energy in agriculture and its percentage share of total electricity consumption from 1982-83 to 2022-23. Additionally, electricity consumption per unit of cropped area (EC/CA) and irrigated area (EC/IA) is analyzed and compared with efficiency of energy in agriculture (EEA), measured by agricultural production per unit of electricity consumed over time.

Electricity consumption per unit of cropped area (EC/CA): Calculates the electricity consumed per unit area of land under cultivation.

$$\frac{EC}{CA} = \frac{\text{Total electricity consumption in agriculture (GWh)}}{\text{Total cropped area (in hectares)}}$$

Electricity consumption per unit of irrigated area (EC/IA): Calculates electricity used per unit of irrigated land.

$$\frac{EC}{IA} = \frac{\text{Total electricity consumption in agriculture (GWh)}}{\text{Total irrigated area (in hectares)}}$$

Efficiency of energy in agriculture (EEA): It is determined by measuring how much agricultural production is generated per unit of electricity consumed.

$$EEA = \frac{\text{Agricultural production (in tons)}}{\text{Total electricity consumption in agriculture (GWh)}}$$

Finally, trends in agricultural electricity consumption are visualized at the disaggregated state level. The analysis uses CAGR and graphical methods in order to offer a thorough analysis of these patterns throughout time, with a focus on understanding changes in energy efficiency alongside electricity consumption.

Association between agricultural growth and electricity use (EC)

A comprehensive econometric framework is employed, including the panel data unit root tests to examine stationarity, panel cointegration analysis to examine long-run relationships between variables, and dynamic panel causality models to explore the direction of causality among the variables.

Tests for stationarity in panel data

Prior to performing a cointegration analysis, verifying the time series data's constancy is essential. Stationarity is a prerequisite for avoiding spurious regression results. For this purpose, to verify the sequence of integration in the GDP and consumption of electricity data series, unit root tests are performed.

Im, pesaran, and shin (IPS) test (Im *et al.* 2003): This test allows for heterogeneity in autoregressive parameters across cross-sections, making it more appropriate given the diverse economic and political contexts of states in the country. The IPS test averages tests for stationarity, non-stationarity and random walk, statistics for each cross-section.

Levin, lin, and chu (LLC) test (Levin *et al.* 2002): Unlike the IPS test, the LLC test assumes homogeneity in the autoregressive parameters across cross-sections.

Tests of Fisher-ADF and Fisher-PP: These non-parametric tests, proposed by (Maddala & Wu 1999), which combine separate unit root tests over cross-sections, offer an alternate method.

The following is the definition for an autoregressive method:

$$y_{it} = \rho_i\, y_{it}\text{-}1 + \delta_t\, X_{it} + e_{it}$$

Where,

y_{it} represents either agricultural GSDP or electricity consumption for state i at time t.
ρ_i indicates the autoregressive coefficient.
X_{it} includes fixed effects and deterministic trends.
e_{it} denotes the error term.

For every test, the alternative hypothesis states that at least one series is stationary, while the null hypothesis states that every series contains nonstationary data.

Panel cointegration tests

To test for long-run equilibrium relationships between electricity consumption and agricultural GSDP, we apply Pedroni's (1999, 2004) heterogeneous panel cointegration test. This test is well-suited for panels characterized by varied cross-sectional error variations and dynamics. The long-run relationship is modelled as:

$$GSDP_{it} = \alpha_{it} + \delta_{it} + \gamma_{1i}\, EC_{it} + e_{it}$$

Where:
α_{it} represents state-specific fixed effects.
δ_{it} captures deterministic trends.
γ_{1i} is the elasticity of use of electricity with respect to agricultural GDP.
Pedroni's test includes two dimensions:

Within-dimension tests: These tests use statistics like the panel ρ, panel v, panel ADF, and panel PP-statistics to pool autoregressive coefficients across states.

Between-dimension tests: The panel ρ-statistic, panel ADF, and panel PP-statistic are group-specific tests that average autoregressive coefficients across states.

Fully modified OLS estimation (FMOLS)

FMOLS is a technique that modifies OLS to account for serial correlation and tests for endogeneity in regressors. It can be used to estimate and test single equation cointegrating relationships and is suitable when all variables attain stationarity after first differencing and are cointegrated.

The FMOLS estimator is used to estimate the long-run parameters of the cointegrated regression model:

$$Y_t = \alpha + \beta\, X_t + \epsilon_t$$

Y_t represents the dependent variable (e.g., GDP).
X_t is the independent variable (e.g., electricity consumption).
α and β are the coefficients to be estimated.
ϵ_t is the error term.

FMOLS is designed to handle the problems associated with estimating long-run equilibrium relationships in the presence of cointegration.

Dynamic panel causality tests

Once cointegration is established, we employ a dynamic panel model with error correction to assess both short-run and long-run causal relationships. The dynamic model takes the following form:

For agricultural GSDP:

$$\Delta GSDP_{it} = \alpha_{1j} + \sum_{q=1}^{k} \theta_{11iq}\, \Delta GSDP_{it-q} + \sum_{q=1}^{k} \theta_{12iq}\, \Delta EC_{it-q} + \lambda_{1i}\, e_{it-1} + e_{1it}$$

For electricity consumption:

$$\Delta EC_{it} = \alpha_{1j} + \sum_{q=1}^{k} \theta_{21iq}\, \Delta GSDP_{it-q} + \sum_{q=1}^{k} \theta_{22\,iq}\, \Delta EC_{it-q} + \lambda_{2\,i}\, e_{it-1} + e_{2\,it}$$

Δ denotes the first difference.
λ_{1i} and λ_{2i} represent the error correction terms, which capture long-run causality.
Short-run causality is tested by evaluating the significance of $\theta_{12\ iq}$ and $\theta_{21\ iq}$ in their respective equations.

The model allows us to test the hypothesis that electricity consumption drives short-term development in agriculture while also considering the reverse causality.

Fixed effect (within) panel data regression model

The district-level data on groundwater extraction and groundwater recharge published in "Dynamic Groundwater Resources of India" for the years 2004, 2009, 2011, 2013, 2020 and 2023 were utilized, which formed an unbalanced panel. Following fixed effect (within) panel data regression. This model was utilized to examine the effect of change in agricultural electricity subsidies in year t and state j on groundwater extraction in district i with district fixed effects Υ_i and year fixed effects λ_t and standard errors clustered at the state. The district and year fixed effects help to control for aggregate time shocks like agricultural policies and fixed district un-observables like topography, soil type.

$$D_{it} = \alpha_0 + \alpha_1 S_{jt} + \alpha_2 R_{it} + \alpha_3 X_{jt} + \lambda_t + Y_i + u_{it}$$
$$i = 1……N \ \text{ and } \ t = 1……. T$$

Where, D_{it} is groundwater irrigation draft (ham), S_{jt} is agricultural electricity subsidy (million Rs.), R_i is groundwater recharge (ham), X_{jt} is a vector of time-varying state observables viz., whether a state election is held in a particular year, annual generation of electricity (Mkwh), losses in transmission and distribution (T&D) (Mkwh) and availability of power supply (hrs per annum), and uit is the error term. This model was estimated by using Stata software.

RESULTS

Electricity usage trends in Indian agriculture

Electricity has emerged as the major energy source in the nation's sector of agriculture. Use of electricity in agriculture has increased from 17,817 GWh (Gigawatt hour) in 1982-83 to 2,40,800 GWh in 2022-23 with a CAGR of 6% over the period. This can be attributed to free power supply for agricultural purposes in many states.

With the thrust towards increasing rural electrification in India, the percentage share of electricity consumption in agriculture to total electricity consumption had shown an increasing trend till the 90s, but after that, the share declined and has become stagnant at around 20%, though the absolute electricity consumption in agriculture has shown a continuously increasing trend (Fig.1).

Electricity consumption in agriculture per unit of cropped area as well as per unit of irrigated area

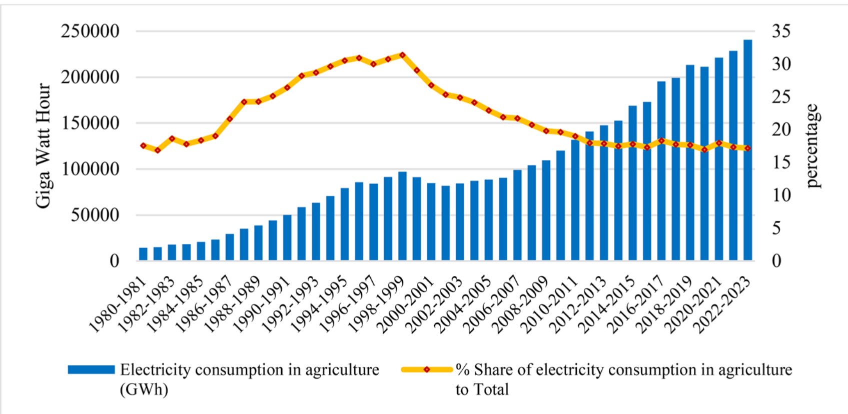

Fig. 1. Electricity consumption in agriculture in India.

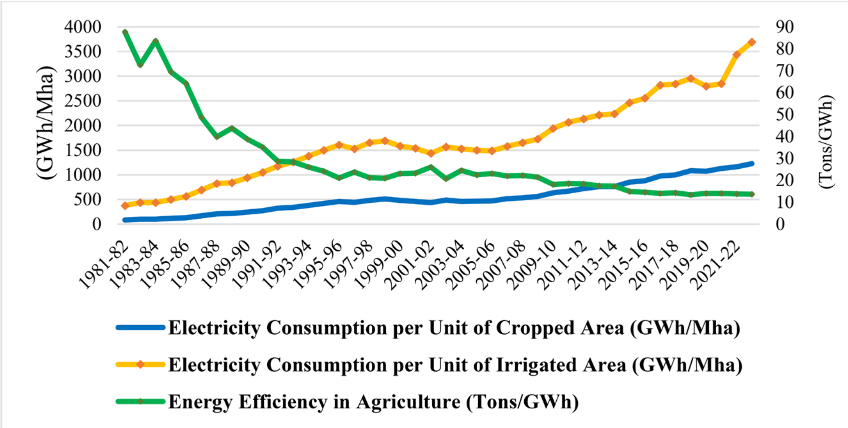

Fig. 2. Energy efficiency and agricultural growth.

has shown a growing pattern at a CAGR of 5.6% and 4.0%, respectively, from 1982-83 to 2022-23 (Fig.2). However, energy efficiency, which can be measured as agricultural production per unit of electricity consumption, has not increased commensurately and has shown a declining trend with a CAGR of -2.8% over the same period. This highlights India's lower efficiency in the amount of electricity used for farming.

The amount of energy used for agriculture in each of India's major states is depicted in Fig. 3. The north-eastern states were found to be having negligible electricity consumption in agriculture per unit of the cropped area. The eastern zone also lies far behind in terms of electricity consumption in agriculture compared to other zones. This might be because these states are using diesel as the energy source for extracting groundwater. The southern states like Andhra Pradesh (which includes Telangana). The highest electricity use for agricultural applications per unit of cultivated land was recorded in Tamil Nadu and Karnataka. This is followed by Punjab and Haryana from the northern zone and Maharashtra and Gujarat from the western zone.

In almost all the major states, there has been a rise in the amount of power used in agriculture per unit of cropped area, which indicates an intensifica-

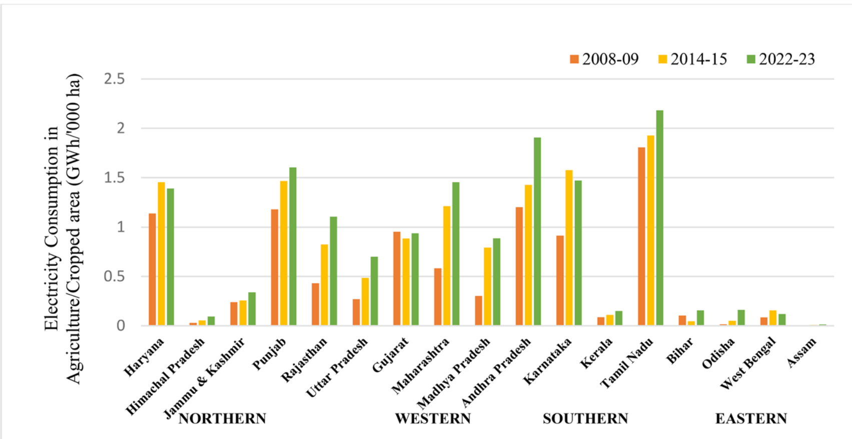

Fig. 3. Electricity consumption in agriculture per unit of cropped area in India.

Table 1. Results of the panel unit root test for national GDP and electricity usage.

Test	GDP		EC	
	Statistic	Probability	Statistic	Probability
	Level		Level	
Levin, Lin, and Chu	0.55	0.71	1.262	0.89
Im, Pesaran, and Shin	-0.24	0.40	0.404	0.65
ADF-Fisher Chi-square	24.99	0.86	56.60	0.64
PP-Fisher Chi-square	26.14	0.83	56.54	0.65
	1st Difference		1st Difference	
Levin, Lin, and Chu	-23.15	<0.001	-22.84	<0.001
Im, Pesaran, and Shin	-18.87	<0.001	-21.84	<0.001
ADF-Fisher Chi-square	325.857	<0.001	375.99	<0.001
PP-Fisher Chi-square	326.212	<0.001	392.63	<0.001

tion of electricity consumption in Indian states for agricultural purposes.

Relationship between agricultural growth and electricity use

First, we examine the sequence of integration in the GDP and electricity consumption data series in order to determine whether agricultural growth (GDP) and electricity consumption (EC) are causally related. The two variables were then tested for long-term correlations using panel cointegration. In order to assess the short-run causality direction, dynamic panel causality was utilized.

Step-1: Panel unit root tests were conducted to assess the stationarity of the electricity consumption (EC) and gross domestic product (GDP) panel data before performing the cointegration analysis. The results, shown in Table 1 show that both series are nonstationary in their initial form at the national level. However, after taking the first difference, both series become stationary, indicating that they are first-order integrated. This result supports moving forward with the cointegration analysis to investigate the connection between agricultural growth and electricity use.

Considering that the two series are order one integrated, it becomes necessary to investigate whether a long-run co-integrating relationship exists between them.

Step-2: Panel cointegration test: To determine whether there is cointegration between GDP and power use, Pedroni's heterogeneous panel cointegration test was employed (Pedroni 2004). This test is particularly useful as it accounts for cross-sectional interdependence while allowing for different individual effects across states. Table 2 displays the findings from the national panel cointegration test.

According to the findings, the majority of the tests reject the null hypothesis that there is no cointegration with significant negative values for the Group PP-Statistic, Group ADF-Statistic, Panel Rho-Statistic, Panel PP-Statistic, and Panel ADF-Statistic. However, the Panel v-Statistic did not support the rejection of the null hypothesis, and the Group Rho-Statistic showed a p-value greater than 0.05, suggesting no cointegration based on that specific test.

Despite these exceptions, the overall results provide strong evidence of a long-run co- integrating correlation between GDP and power consumption in India's major states. This implies that, after accounting for state-specific factors, over time, there is a

Table 2. Results of panel cointegration tests for Indian states.

Test	Statistic	Probability
Panel v-Statistic	-1.73	0.95
Panel Rho-Statistic	-2.51	<0.001
Panel PP-Statistic	-4.29	<0.001
Panel ADF-Statistic	-4.23	<0.001
Group Rho-Statistic	-0.73	0.23
Group PP-Statistic	-2.23	<0.001
Group ADF-Statistic	-1.99	<0.001

Table 3. Panel FMOLS estimation results.

Test	Coefficient	t -Statistic	Probability
Panal FMOLS	0.245	3.975	<0.01

Table 4. Panel causality test (dependent variable: GSDP).

	ETC	Long-run causality t-Statistics	Long-run causality Probability	Short-run causality t-Statistics	Short-run causality Probability
National level	−0.028	−2.83496	0.016	1.983	0.006

correlation between actual GDP and electricity use highlighting the importance of electricity as a driving factor in agricultural growth.

Across the major Indian states, the panel Fully Modified Ordinary Least Squares (FMOLS) test results show a substantial and positive long-term association between real Gross Domestic Product (GDP) and power consumption. The coefficient for power usage is 0.245, which is statistically significant at the 1% level, according to the estimation findings, which are shown in Table 3. This implies that there is a 0.245% increase in real GDP for every 1% increase in electricity use. Electricity consumption in India's major states is co-integrated with the GDP from agriculture and related sectors, according to the results of the national-level panel cointegration test.

Step-3. After establishing that power consumption and agricultural growth are co-integrated, the short- and long-term causal relationships between the two variables are examined using a panel-based error correction model.

Table 4 displays the outcomes of both short-term and long-term causation. The estimation of a panel vector error correction model shows that there is long-term causality between electricity use and agricultural and related GSDP at a 5% level of significance. Short-run causality is also present, using the Wald test (Kumar *et al.* 2022). Energy consumption is essential to agricultural growth, as seen by the positive relationship between electricity use and agricultural growth.

Effects of groundwater use caused by agricultural electricity subsidies

The effect of change in agricultural electricity subsidy in a particular state and year on groundwater extraction in a district was estimated by using the fixed-effect panel data regression with district and year fixed effects and standard error clustered at the state.

The district and year fixed effects help to control for aggregate time shocks and fixed district un-observables like topography, soil type. Some other independent variables were also included like

Table 5. Coefficients of determinants of groundwater irrigation draft.

Particulars	Coefficients (Model 1)	Coefficients (Model 2)	Coefficients (Model 3)	Coefficients (Model 4)	Coefficients (Model 5)
Constant	17168.15*** (1629.01)	17151.94*** (1776.42)	14258.04*** (2335.55)	14126.62*** (2345.72)	11465.13*** (4035.09)
Agricultural electricity subsidy (million)	0.056** (0.024)	0.056** (0.0245)	0.046* (0.026)	0.044* (0.026)	0.048* (0.026)
Groundwater recharge (ham)	0.326*** (0.017)	0.326*** (0.017)	0.343*** (0.017)	0.344*** (0.017)	0.342*** (0.017)
Gross generation of electricity (Gwh)	-	0.001 (0.029)	-0.011 (0.031)	-0.009 (0.031)	-0.009 (0.031)
T & D losses (Gwh)	-	-	0.288* (0.147)	0.309** (0.151)	0.308** (0.151)
Power supply (hours/day)	-	-	-	-	1046.02 (1290.26)
Fixed effects	Year, district	Year, district	Year, district	Year, district	Year, district
R square	0.405	0.405	0.396	0.396	0.403
Observations (No.)	1887	1887	1887	1887	1887

Note: Figures in parentheses are standard errors. ***, ** and * denote 1, 5 and 10% level of significance, respectively.

groundwater recharge in a particular district which may affect groundwater extraction. Some other time-varying state observables were also included, like whether a state election is held in a particular year, annual generation of electricity (Gwh), losses of transmission and distribution (Gwh) and availability of power supply (hrs/day). Initially, the model was estimated by taking agricultural electricity subsidy and groundwater recharge as independent variables. Subsequently, other independent variables were included in the model to examine their effects and for a better fit of the model.

As shown in the Table 5 the results of the estimation of the groundwater irrigation draft on agricultural electricity subsidy controlling for fixed district and year un-observables. The coefficient of interest i.e., the coefficient of agricultural electricity subsidy doesn't change much upon including the other independent variables. It was found that agricultural electricity subsidy significantly affects groundwater extraction, and for each one million Rs increase in agricultural electricity subsidy, on an average groundwater extraction increases by 0.048 ham. The coefficient of groundwater recharge was also found significant, and for each one ham increase in groundwater recharge, on an average groundwater irrigation draft was found to increase by 0.342 ham. T & D losses were also found to be a significant factor in influencing groundwater extraction, and for one Gwh increase in T & D losses, on an average groundwater extraction was found to increase by 0.308 ham. The other control variables were not found significant.

DISCUSSION

Energy use and agricultural output have a complex relationship, according to this study of electricity consumption in Indian agriculture. Although electricity consumption has grown significantly, with an average annual growth rate of 6% between 1982 and 2023, agricultural output has not increased in line with this expansion (CEA 2023c). This disparity highlights inefficiencies in energy utilization within the sector, driven largely by systemic and policy-related factors (Shah *et al*. 2012). A major contributor to inefficiency is the shift from canal-based irrigation to groundwater extraction, which now accounts for about 70% of total irrigation in India (Central Ground Water Board 2023). This transformation was facilitated by subsidized and unmetered electricity, leading to over-extraction of groundwater and inefficient energy usage. For instance, farmers often operate pumps for extended periods due to low-quality power supply and lack of metering, resulting in energy wastage (Shah *et al.* 2021).

Additionally, the number of electric and diesel-operated pumps has surged, rising from approximately 12 million in 1990 to over 25 million in 2020 (Energy Statistics 2023). While this expansion has supported agricultural growth, it has also exacerbated inefficiencies, as groundwater irrigation requires significantly more energy than surface irrigation systems. The paper emphasizes the significance of technical interventions and strategic energy policies in addressing these inefficiencies. There is evidence from other nations that innovative irrigation methods, like sprinkler and drip systems, have the ability to improve water and energy efficiency. For example, a study by Sivanappan (2019) indicated that these systems can reduce water usage by up to 40% and energy consumption by 30%, while increasing crop yields by 20–30%. Despite their advantages, barely ten percent of India's irrigated land is covered by these methods, suggesting significant scope for expansion.

Integrating renewable energy solutions, particularly solar-powered irrigation pumps, could further address inefficiencies. India's PM-KUSUM scheme aims to install 2 million solar pumps by 2025, potentially saving 25 billion units of electricity annually and reducing the burden on state electricity boards (PIB 2024). These measures align with global trends, where renewable energy in agriculture has proven to be a game-changer for sustainable practices. The current electricity subsidy regime has unintentionally incentivized overuse and inefficiency. Studies estimate that electricity subsidies for agriculture accounted for approximately ₹70,000 crore in 2022, comprising 15% of total state power subsidies (Jha *et al.* 2012). Supporting farmers to use more efficient methods may be achieved by linking subsidies to metered usage.

Evidence from Gujarat's Jyotigram Scheme was launched in September 2003, which provides separate power lines for agriculture and households, showing that metering and rationing electricity for agriculture led to reduced wastage and improved groundwater sustainability without adversely affecting productivity (Shah *et al.* 2008).

Poor-quality and unreliable power supply is another challenge contributing to inefficiencies. Studies indicate that agricultural feeders in India face voltage fluctuations and outages lasting up to 8–10 hours daily in peak seasons (CEA 2023b). Investments in grid infrastructure, including dedicated agricultural feeders and energy-efficient transformers, are critical to improving reliability and reducing losses. For instance, Agricultural feeder separation energy efficiency projects in Tamil Nadu reduced transmission losses by fifteen per cent and increased production.

Beyond inefficiencies, excessive electricity consumption for groundwater extraction has raised concerns about environmental sustainability. Over-extraction has led to groundwater depletion at alarming rates, with the water table declining by 1–2 meters annually in states like Punjab and Haryana (Central Ground Water Board 2023). This has implications for long-term agricultural viability and energy demand.

Furthermore, there is a positive correlation between agricultural expansion and electricity use. According to the study's findings, a one percent rise in electricity use results in a 0.24% rise in agricultural GDP, confirming the hypothesis of reliant on energy growth. However, the diminishing returns to energy usage highlight the urgent need for policies prioritizing efficiency and sustainability. Despite its contributions, the study has certain limitations. Historical data may not fully capture recent technological advancements or regional disparities in energy use and agricultural practices. Future studies have to concentrate on gathering facts in real time periods and regional case studies to provide actionable insights. Exploring the role of emerging technologies like artificial intelligence and IoT in optimizing irrigation and energy usage could further advance policy measures. Additionally, examining the socio-economic implications of energy reforms, especially for marginal and small farms, is essential. For instance, while metered electricity may promote efficiency, it could also impose financial burdens on resource-poor farmers, necessitating targeted support measures.

CONCLUSION

In conclusion, electricity consumption is an important motivator of agricultural growth in India, yet inefficiencies in its utilization remain a significant challenge. The shift towards groundwater irrigation, facilitated because unrestricted and subsidized electricity has, has led to excessive energy consumption and resource overuse. Addressing these inefficiencies requires promoting advanced irrigation innovations like sprinkler and drip systems, which can reduce both energy and water use. Additionally, integrating renewable energy solutions like solar pumps under programs like the PM-KUSUM scheme offers a sustainable pathway to reduce dependence on conventional electricity while mitigating environmental impacts.

Policy reforms are essential to link subsidies with metered consumption, thereby encouraging responsible energy use and discouraging wasteful practices. For farms, more efficiency and lower operating costs can be achieved through improved power infrastructure and a steady supply of electricity. By coordinating energy regulations with sustainable farming methods and water management India can achieve a balance between productivity growth and environmental conservation, ensuring the long-term sustainability of its agricultural sector.

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