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The impact of reliable electricity access on agricultural income and land utilization in China

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ABSTRACT

Reliable electricity access is crucial for agricultural production, as it ensures a constant supply of electricity for power and automation. This study investigates the impact of reliable electricity access on agricultural income and land utilization in China. By combining household panel data from the 2012–2018 China Labor-Force Dynamics Survey with wind power data from the National Energy Administration and local geographic information, we measure the reliability of electricity supply through power outages. These outages are instrumented using feed-in tariff rates, curtailment rates of wind power, and interactions between curtailment rates and both the mean and standard deviation of a city's elevation. Our findings reveal that reliable electricity access significantly boosts grain income. Specifically, it increases estimated grain income by 5303 yuan, equivalent to approximately 13.8 % of total household income. The key mechanism driving this increase is the expansion of irrigated farmland by 4.57 mu. This study provides important insights for policymakers aiming to improve rural electrification.

1. Introduction

Electricity is a critical input for production (World Bank, 2021), and its reliable access has been extensively studied within the industrial sectors of developing countries (Alby et al., 2013; Fisher- Vanden et al., 2015; Allcott et al., 2016; Abeberese et al., 2021). However, the agricultural sector's reliance on electricity has received much less attention. Reliable electricity access can significantly enhance agricultural growth by facilitating the adoption of electrical equipment and digital technologies, thereby boosting labor productivity. Moreover, transitioning from oil-powered to electrical equipment—particularly when renewable energy constitutes a substantial part of a nation's electricity supply—can help the agricultural sector reduce greenhouse gas emissions and amplify the impact of energy transformation on climate change mitigation.

China provides an ideal context for exploring the interactions among reliable electricity access, renewable energy development, and agricultural production. The growth of agricultural mechanization has expanded the application scope of electricity in production, establishing a strong connection between electricity input and agricultural output. According to the statistical data from China's agricultural machinery industry, electric motor power increased by 22 % from 2010 to 2020, compared to a 14 % increase in total power.[1] Considering irrigation facilities that use electricity as an example, the share of irrigated land areas adopting drip irrigation rose from 3.5 % in 2010 to 9.3 % in 2017 (Wang et al., 2019). On the other hand, although China's electricity access rate has reached 100 % since 2015,[2] the electricity supply remains unreliable with power outages (Guo et al., 2023), which challenges the high-intensity use of electrical equipment during specific farming seasons.[3] A potential source of the outage might due to the

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[1] The data come from China agricultural machinery industry yearbooks.

[2] In 2013, the National Energy Administration (NEA) made a three-year action plan (2013–2015) to solve the electricity consumption problem for the last 2.73 million people without electricity access. By the end of 2015, the NEA announced the successful completion of the task. Relevant news can be found on the official website of the Chinese government at https://www.gov.cn/xinwen/2015-12/25/content_5027715.htm.

[3] In terms of residential electricity consumption, Bajo-Buenestado (2021) and Meek et al. (2023) provide relevant evidence on the impacts of electricity quality on service consumption and appliance adoption in Kenya and the Kyrgyz Republic, respectively.

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integration of the intermittent renewables, which can affect the local power reliability as well as the agriculture production decisions of local farmers. Therefore, our study focuses on reliable electricity access in China and investigates its impact on rural households' crop income and various agricultural inputs using panel data from the 2012–2018 China Labor-Force Dynamics Survey (CLDS).

For a household, reliable electricity access and agricultural production decisions may be simultaneously correlated with unobserved household characteristics and local conditions. We instrument the reliability of household electricity access using variables related to wind power integration. The exogeneity of our instrumental variables (IVs) is primarily justified by the fact that wind power and agricultural production are managed by separate governmental agencies that have limited coordination.

Wind power affects the reliability of electricity supply in two primary ways. First, an increase in wind power raises the likelihood of requiring flexible adjustment services, which can threaten the reliability of electricity supply. Second, the amount of the curtailed wind power reflects the adjustment capability of the power grid; a grid with limited adjustment capability is more likely to curtail wind power, thereby decreasing the likelihood of reliable electricity supply. To address the endogeneity problem, we employ IVs corresponding to these two measures. Moreover, higher average elevation is associated with more consistent wind patterns, whereas complex terrain can increase turbulence, destabilizing energy generation (Bechtle et al., 2019; Radünz et al., 2020; Laleva, 2024). Therefore, we also use interactions between these two elevation-related variables and the wind curtailment rate as IVs to capture how geographical heterogeneity moderates grid stability challenges under varying wind power intermittency.

We find that reliable electricity access significantly increases grain income by 5303 yuan, which is about 13.8 % of the total household income. An investigation of various agricultural inputs indicates that the primary driver of this increase in crop income is the expansion of irrigated farmland. Specifically, access to reliable electricity enhances the area of irrigated farmland by 4.57 mu. In contrast, we observe no significant changes in the operating area of dry farmland, nor do we find notable effects on labor input or tractor ownership. Furthermore, we explore three potential mechanisms that may explain the increase in irrigated farmland area. First, we assess whether households lease in irrigated farmland from others. Second, we investigate whether households reduce the amount of abandoned irrigated farmland. Third, we examine whether households convert other types of agricultural land into irrigated farmland. Our results support the second mechanism, indicating that reliable access to electricity promotes more efficient use of agricultural land. Finally, we conduct three sensitivity checks using additional control variables and varying sample restrictions. Specifically, we include household control variables, exclude households without electricity access, or add cross-sectional households observed only once during the study period. In general, our findings remain robust under these different conditions.

Our study contributes to the literature in two key ways. First, we extend the research on reliable electricity access and economic development by focusing on the agricultural sector, which has received comparatively less attention than the industrial sector. While prior studies have documented the negative effects of power outages on firm performance—such as reduced sales (Cole et al., 2018), productivity (Elliott et al., 2021), R&D investment (Guo et al., 2023), and employment (Mensah, 2024)—evidence from agriculture remains limited. This gap may arise from the preconditions needed to causally identify the impact on agricultural production, such as variations in electricity supply quality and the relatively large-scale use of electrical equipment, which are often absent in rural areas of developing economies. Most existing studies in developing countries have instead concentrated on the broader effects of electrification (i.e., the accessibility of electricity) on human capital, non-farm employment, and social welfare (e.g., Lipscomb et al., 2013; Dinkelman, 2011; Lee et al., 2020; Burlig and Preonas, 2024). Exceptions include studies from India that examine electricity use for irrigation and its environmental trade-offs (Shah, 2007; Banerji et al., 2012; Badiani-Magnusson and Jessoe, 2018). Our study builds on this line of work by offering new empirical evidence on how electricity reliability—rather than just access—affects agricultural production.

Second, we contribute to the growing literature on the intersection of renewable energy integration, electricity reliability, and agricultural sustainability. While concerns about the intermittency of renewables have been well explored through ex-ante modeling (e.g., Gowrisankaran et al., 2016), few studies have empirically examined the ex-post effects of renewable energy deployment on electricity system stability (Csereklyei et al., 2021). Simultaneously, there is increasing recognition of the need for integrated energy-agriculture strategies to meet global climate and development goals (IRENA and FAO, 2021). However, most work on renewable energy in agriculture has focused on small-scale technical feasibility rather than system-wide impacts (Barbier, 2020; IRENA, 2022). Addressing this gap, our study uses China's wind power policy and curtailment rates as IVs to identify the impact of reliable electricity access on agricultural production.

The remainder of this paper is organized as follows. Section 2 briefly introduces the development of rural power grids in China and highlights the existing problems. Section 3 describes the data and samples used in our analysis. Section 4 presents the identification strategy. In Section 5, we examine the main results, discuss the underlying mechanisms, and conduct robustness checks that render additional validity to our identification. Finally, Section 6 concludes the study.

2. Background

Since the reform and opening up in 1978, the development of rural power grids in China has evolved through four distinctive phases. In the first phase (1978–1997), local governments primarily led the construction and maintenance of rural power grids, with limited investment from the central government. Due to insufficient public investment, rural power grids below the township level were often financed by farmers, resulting in a low-quality electricity supply (Ding et al., 2018). To address this problem, the central government initiated several upgrading projects during the second phase (1998–2005). Provincial power companies took charge of planning, constructing, managing, and operating rural power grids. With an investment of 290 billion yuan, the quality of these grids improved significantly; for instance, the overall wire loss in low-voltage grids decreased from 20 % to less than 12 % during this period (Bie and Lin, 2015). While continuing to upgrade rural power grids, the third phase also prioritized achieving universal electricity access, which was accomplished by the end of 2015. In the fourth phase (2016 to present), the central government has launched two new rounds of upgrading projects. The first round (2016–2020) aimed to provide reliable electricity supply in rural areas nationwide, while the second round, initiated in 2021, focuses on promoting the digital and intelligent development of rural power grids.[4]

Despite China's enormous efforts to upgrade rural power grids and strengthen the application of new technologies in power grid upgrades, three factors continue to challenge reliable electricity supply in rural areas. First, the lack of careful design in initial constructions and the overall low quality of equipment complicate power grid upgrades (Chen and Zhang, 2019). Second, rural power grids with low load density and scattered users require long transmission and distribution lines, leading to issues such as heavy overload, low voltage, high energy loss, and difficult maintenance. As a result, even within the same village, there are

[4] The key government documents can be found on the official website of the Chinese government at https://www.gov.cn/gongbao/content/2016/content_5051227.htm and https://www.gov.cn/gongbao/2023/issue_10626/202308/content_6897065.html.

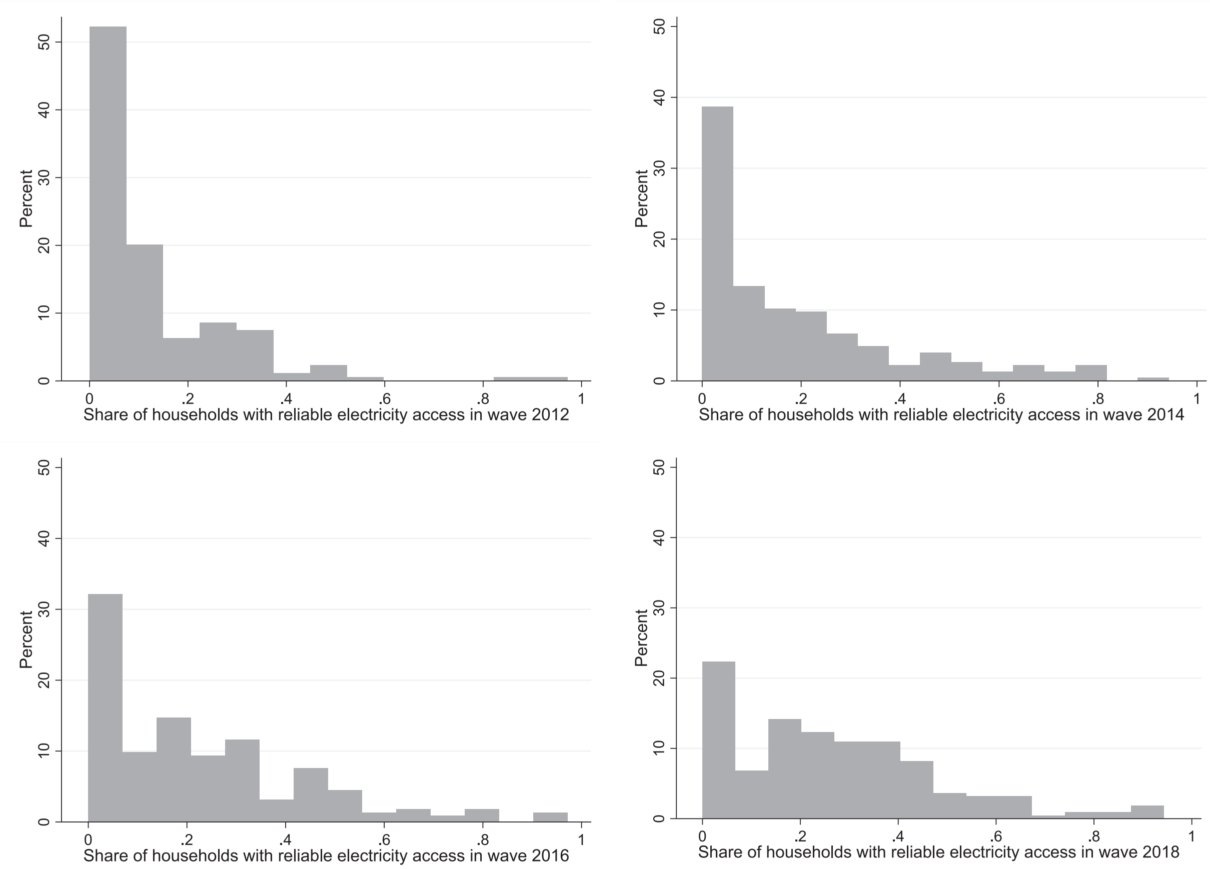

Fig. 1. Distribution of reliable electricity access within the village.

differences in the quality of electricity supply across households. As shown in Fig. 1, using CLDS data, while more rural households have gained access to reliable electricity over time, these households are not concentrated in a few villages, and the within-village difference in electricity supply has not significantly narrowed. Third, agricultural production is characterized by seasonality. Rural power grids must meet the high electricity demand during the farming season (Tang et al., 2023). Hence, as the farming season approaches each year, there are numerous news reports about power grid companies providing maintenance services.[5]

3. Data and sample

We combine data from four sources for analysis: rural household and village data from the CLDS, weather data from the Institute of Geographic Sciences and Natural Resources Research (GSNR) under the Chinese Academy of Sciences, elevation data from the National Aeronautics and Space Administration (NASA), and wind power data from the National Energy Administration (NEA).

The CLDS is a national survey conducted every two years in 2012, 2014, 2016, and 2018, covering 29 provinces and equivalents (including directly administered municipalities and autonomous regions) in mainland China.[6] A rotating sample design, tracking approximately 60 % of households between two waves, enables the construction of a household panel from this database. In addition to basic household and village characteristics, the CLDS contains information on household electricity access and agricultural production for the rural sample. Although we cannot determine whether experiences of power outage came from agricultural production or daily life, our estimates, if there is any bias, should be downward biased, as power outages in daily life should have less impact on agricultural production.

The weather database covers consecutive daily weather records from 2479 monitoring stations across 31 provinces, including daily temperature, precipitation, wind speed, sunshine duration, and relative humidity. We measure city-level daily weather conditions by taking an inverse-distance weighted average of all weather variables from stations located within a 200 km radius of each city's centroid, where the weights are the inverse of their squared distance to each city so that more distant stations are given less weight (Deschênes and Greenstone, 2011).[7]

The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) with a resolution of 90 m. To calculate the average elevation and standard deviation of elevation for each city using SRTM data, we first extracted the elevation data for the defined area.

[5] Relevant news reports can be found on the websites of branches of the State Grid Corporation of China, such as http://www.ln.sgcc.com.cn/html/main/col32/2018-07/17/20180717100756708270006_1.html, https://www.sc.sgcc.com.cn/html/main/col37/2016-03/28/20160328154128358254578_1.html, http://www.he.sgcc.com.cn/html/main/col9/2021-03/30/20210330090629490675034_1.html, and http://www.sn.sgcc.com.cn/html/sl/col677/2024-03/15/20240315164444998397294_1.html.

[6] The survey collected data in the previous year, so the dataset contains information from 2011, 2013, 2015, and 2017.

[7] CLDS county codes have been randomized to protect the privacy of respondents. CLDS city is the smallest administrative unit that can be merged with data from other sources.

The average elevation was computed by summing all the elevation values and dividing by the total number of valid data points. Concurrently, the standard deviation was calculated to assess the variability in elevation within the city; this was done by determining the square root of the variance, which indicates how much the elevation values deviate from the mean.

The wind power data are obtained through documents publicly released by the NEA, including the feed-in tariff rates by resource category and the provincial curtailment rates of wind power. To promote the development of wind power, the feed-in tariff rates roughly reflect the investment costs based on wind resource endowments and the costs of wind power equipment (more policy details can be found in Appendix 1). While all provinces installed wind power during the years in our sample, there are variations in the proportion of curtailed wind power between different locations and years (Appendix Table 2).

For our main analysis, we focus on rural panel households observed at least twice, including 6984 households with complete information.[8] Table 1 shows the descriptive statistics of household electricity access and the outcome variables related to agricultural production. The electricity access rate in rural China is very high, with only 1 % of households in our sample reporting no electricity access. Moreover, electricity suppliers have improved the reliability of their services, suggested by the fact that the proportion of households that have never experienced power outages within a year doubled, from 12 % in 2011 to 26 % in 2017. However, probably because of the rapid structural transformation, the growth in agricultural production did not coincide with the improvement in rural electricity supply. The proportion of households engaged in agricultural production decreased from 73 % in 2011 to 56 % in 2017. Although agricultural machinery (e.g., tractors) seems to have replaced labor to some extent, the average size of operating farmland has decreased with an increase in abandoned areas. Operating dry farmland (i.e., farmland without irrigation facilities) experienced a larger reduction than irrigated farmland. With a reduction of 20 %, the area of dry farmland operated by rural households declined from 2.39 mu in 2011 to 1.91 mu in 2017. During the same period, the operating area of irrigated farmland dropped from 1.52 mu in 2011 to 1.35 mu in 2017, while the operating area of horticultural land experienced a slight increase from 0.17 mu in 2011 to 0.19 mu in 2017. Consequently, the crop income obtained by rural households decreased. Grain income fell from 2849 yuan in 2011 to 2144 yuan in 2017, while cash crop income declined from 1057 yuan in 2011 to 812 yuan in 2017.[9]

Table 2 reports descriptive statistics on household characteristics and local conditions that may affect or coincide with the improvement of rural electricity supply and the changes in agricultural production shown in Table 1. In line with the decreasing household labor for agricultural production, rural households in our sample have been aging. The proportion of old people over the age of 60 increased by 15 % from 2011 to 2017. At the village level, infrastructure construction has been strengthened, with its likelihood of accounting for the top three financial expenditures increasing by 12 %. Finally, there have been some changes in local weather conditions. The sample areas have become warmer and wetter on average.

4. Identification strategy

Our baseline estimation equation is given by:

$$Y_{ijkpgt} = \beta RE_{it} + X_{jt}\gamma_1 + Z_{kt}\gamma_2 + \alpha_i + \mu_{gt} + \epsilon_{ijkpgt} \tag{1}$$

where Y_{ijkpgt} is the outcome variables related to agricultural production for household i in village j, city k, and province p, covered by grid g in year t.[10] We control for the two-way fixed effects. α_i is a collection of household fixed effects that capture household and local time-invariant conditions. μ_{gt} is a set of grid-year fixed effects that absorb common and grid-specific annual trends. RE_{it} is a binary variable for reliable electricity access, equaling one if the household had no power outages in year t, and zero if it had no electricity access, or experienced frequent or occasional power outages in year t.[11] β is the parameter of interest that captures the impact of reliable electricity access on agricultural production.

Since household electricity access and agricultural production decisions may be correlated with unobserved household characteristics and local conditions, we employ an IV approach to address endogeneity. Our identification strategy leverages the unique characteristics of wind power generation and its integration into the electricity grid. Wind power, as an intermittent renewable energy source, is inherently volatile and cannot be manually controlled. This volatility necessitates frequent adjustments by other energy generators to balance electricity supply and demand in real time. However, during our study period, China's compensation mechanism for such adjustments relied on administrative planning (Li et al., 2024), which lacked economic incentives and flexibility. Although the 2006 Renewable Energy Law mandated grid companies to purchase the full amount of renewable energy, grid operators often curtailed wind power to maintain a stable and controllable electricity supply (Liu et al., 2018).

Our IVs are all grounded in institutional and geographical features of wind power development. The first-stage equation is given by:

$$\begin{aligned} RE_{ijkpgt} = {} & \delta_1 FIT_{kt} + \delta_2 CR_{pt} + \delta_3 CR_{pt}{}^*AE_k + \delta_4 CR_{pt}{}^*SDE_k + X_{jt}\theta_1 + Z_{kt}\theta_2 \\ & + \alpha_i + \mu_{gt} + \varepsilon_{ijkpgt} \end{aligned} \tag{2}$$

where the IVs are FIT_{kt}, CR_{pt}, $CR_{pt}{}^*AE_k$, and $CR_{pt}{}^*SDE_k$. Specifically, FIT_{kt} represents the feed-in tariff rate for wind power for city k in year t. CR_{pt} denotes the wind curtailment rate for province p in year t. AE_k and SDE_k indicate the average elevation and the standard deviation of elevation for city k, respectively.

We can classify the IVs into three groups. First, the feed-in tariff rate for wind power (FIT_{kt}) is a central policy mechanism designed to incentivize renewable energy adoption. Higher feed-in tariffs enhance the financial viability of wind projects, spurring capacity expansion and generation. However, elevated wind power integration introduces operational complexities in maintaining real-time grid balance, thereby diminishing supply reliability. Critically, the feed-in tariff is determined exogenously by the central government based on regional wind power potential, rendering it uncorrelated with localized agricultural production.

Second, we adopt the wind curtailment rate as an instrument (CR_{pt}). Under China's guaranteed purchase policy for renewable energy, higher curtailment rates signal insufficient grid flexibility to accommodate intermittent wind power, directly impairing supply reliability. As curtailment decisions are governed by technical and institutional

[8] 60 % of the households are observed twice, 33 % of the households are observed three times, and 7 % of the households are observed four times.

[9] The income from different sources in different years is measured using 2011 prices.

[10] China has three power grid operators, the State Grid Corporation of China (SGCC), the China Southern Power Grid (CSPG), and the Inner Mongolia Power Company (IMPC, usually called the western Inner Mongolia power grid). As the SGCC is much larger than the other two operators, covering 26 provinces and equivalence (including directly administered municipality and autonomous regions), we use its six regional power grids with the CSPG and the IMPC to construct dummy variables for power grid g.

[11] Please note that we have a binary endogenous variable, but we do not use non-linear regressions for the IV estimation to avoid the forbidden regression problem. Following Angrist and Pischke (2008), we use the standard 2SLS which has a linear probability model in the first stage.

Table 1
Descriptive statistics on household electricity access and agricultural production.

	All waves	Wave 2012	Wave 2014	Wave 2016	Wave 2018
Electricity access					
No power outages last year (0/1)	0.19	0.12	0.17	0.21	0.26
	(0.39)	(0.32)	(0.38)	(0.41)	(0.44)
No electricity access last year (0/1)	0.01	0.00	0.01	0.01	0.01
	(0.08)	(0.06)	(0.08)	(0.08)	(0.07)
Outcomes related to agricultural production					
Engaged in agricultural production last year (0/1)	0.63	0.73	0.64	0.59	0.56
	(0.48)	(0.44)	(0.48)	(0.49)	(0.50)
Number of agricultural labor last year	1.15	1.40	1.17	1.05	0.99
	(1.23)	(1.68)	(1.09)	(1.06)	(1.05)
Had tractor last year (0/1)	0.87	0.85	0.87	0.87	0.89
	(0.33)	(0.35)	(0.33)	(0.34)	(0.31)
Operating area of irrigated farmland last year (mu)	1.43	1.52	1.49	1.35	1.35
	(3.03)	(2.66)	(3.28)	(2.84)	(3.25)
Operating area of dry farmland last year (mu)	2.07	2.39	2.00	2.01	1.91
	(4.61)	(4.80)	(4.19)	(4.98)	(4.43)
Operating area of horticultural land last year (mu)	0.17	0.17	0.18	0.15	0.19
	(1.28)	(1.15)	(1.52)	(1.07)	(1.29)
Operating area of grassland & forestland last year (mu)	0.67	0.77	0.80	0.51	0.63
	(7.12)	(3.20)	(11.82)	(3.84)	(3.34)
Leased area of irrigated farmland last year (mu)	0.11	0.13	0.13	0.10	0.09
	(1.14)	(0.94)	(1.61)	(0.86)	(0.78)
Leased area of dry farmland last year (mu)	0.27	0.19	0.26	0.34	0.25
	(2.93)	(1.38)	(2.82)	(3.92)	(2.46)
Leased area of horticultural land last year (mu)	0.01	0.01	0.01	0.01	0.00
	(0.20)	(0.27)	(0.17)	(0.21)	(0.08)
Leased area of grassland & forestland last year (mu)	0.07	0.01	0.17	0.05	0.02
	(6.32)	(0.29)	(11.16)	(2.81)	(0.52)
Abandoned area of irrigated farmland last year (mu)	0.55	0.34	0.60	0.59	0.63
	(1.69)	(1.24)	(1.81)	(1.74)	(1.81)
Abandoned area of dry farmland last year (mu)	0.68	0.35	0.70	0.85	0.74
	(3.45)	(1.59)	(3.49)	(4.44)	(3.05)
Abandoned area of horticultural land last year (mu)	0.07	0.07	0.06	0.08	0.05
	(0.95)	(1.18)	(0.95)	(0.99)	(0.48)
Abandoned area of grassland & forestland last year (mu)	0.26	0.27	0.20	0.32	0.27
	(2.64)	(3.75)	(1.66)	(2.57)	(2.57)
Income from grain (yuan) †	2533.9	2848.6	2676.1	2424.9	2143.9
	(5352.6)	(5150.2)	(5519.3)	(5398.9)	(5198.3)
Income from cash crops (yuan) †	889.1	1057.2	852.8	859.7	811.8
	(6206.7)	(5413.7)	(6945.3)	(6100.4)	(5936.1)
Total household income (yuan) †	38,226.0	26,633.1	41,893.7	38,986.1	43,739.1
	(96,914.1)	(63,290.5)	(121,140.3)	(71,319.1)	(116,111.9)
Essential household expenditures (yuan) †	11,346.4	8952.8	11,782.4	12,007.7	12,195.2
	(18,794.3)	(12,068.4)	(20,148.1)	(17,046.4)	(24,182.3)
Number of observations	17,215	3547	5178	5192	3298

Note: One mu is 1/15 ha. Variables marked by † are deflated using the 2011 price. According to data from the World Bank, the official exchange rate of the Chinese Yuan to the US Dollar was 6.26 in 2011. Standard deviations are reported in parentheses.

constraints within the power sector—rather than agricultural conditions—this variable provides exogenous variation in electricity reliability.

Third, we construct two interaction terms: $CR_{pt}*AE_k$ and $CR_{pt}*SDE_k$. These interactions capture how geographical heterogeneity moderates grid stability challenges under varying wind power intermittency. Higher average elevation is associated with more consistent wind patterns, while complex terrain can lead to increased turbulence, which destabilizes energy generation (Bechtle et al., 2019; Radünz et al., 2020; Laleva, 2024). Thus, for a given curtailment rate (reflecting grid adjustment capacity), cities with higher mean elevation and lower elevation dispersion experience more stable wind output, enhancing supply reliability. Although elevation can also impact agricultural production, it is a fixed characteristic over time and has been absorbed by household fixed effects.

The exogeneity of our IVs is primarily justified by the fact that wind power and agricultural production are managed by separate governmental agencies that have limited coordination. To reduce the reliance on fossil fuels and increase energy independence, the Chinese government has promoted renewable energy including wind power since early 2000. A key policy is the feed-in tariff introduced in 2009. Wind farm investors receive a fixed sell price determined by the National Development and Reform Commission.[12]

The policy divides the whole country into four categories based on the geographical distribution of wind resources and project engineering-related factors. Key considerations include the average wind speed and capacity factor in a given region, which determine the potential efficiency of wind power generation. In addition, the ease of grid connection and the local grid's ability to absorb wind energy play important roles. A single province could have more than one rate if it belongs to different resource regions. After the introduction of the feed-in tariff in 2009, the rates were not changed until 2015. After that, the rates were reduced again in 2016 and 2018, as summarized in Appendix Table 1.

[12] The evolution of China's wind power pricing policies can be roughly classified into three stages. The first stage was before 2003, when there was very little wind power production and prices were mostly approved by the government on a case-by-case basis. The second stage was between 2003 and 2008, when a concession-bidding pricing policy and approval-pricing policy co-existed. During this period, the Chinese central government conducted wind concession programs for large-scale wind farms. The bidding price later became the basis for building new wind power projects for provinces that already had experience (Qiu and Anadon, 2012).

Table 2
Descriptive statistics on household characteristics and local conditions.

	All waves	Wave 2012	Wave 2014	Wave 2016	Wave 2018
Household characteristics					
Household size	3.01 (1.56)	3.15 (1.50)	3.08 (1.59)	2.97 (1.56)	2.82 (1.57)
Share of female household members	0.50 (0.25)	0.50 (0.23)	0.51 (0.24)	0.50 (0.25)	0.50 (0.27)
Share of children (0–15)	0.15 (0.20)	0.15 (0.20)	0.15 (0.20)	0.15 (0.20)	0.13 (0.20)
Share of adults (16–60)	0.55 (0.37)	0.62 (0.35)	0.56 (0.36)	0.52 (0.37)	0.50 (0.39)
Share of elderly (>60)	0.30 (0.38)	0.22 (0.34)	0.28 (0.37)	0.33 (0.39)	0.37 (0.41)
Local economic conditions					
Village had non-agricultural economy last year (0/1)	0.25 (0.43)	0.33 (0.47)	0.22 (0.42)	0.24 (0.43)	0.23 (0.42)
Share of village expenditure on infrastructure ranked among the top three last year (0/1)	0.60 (0.49)	0.60 (0.49)	0.53 (0.50)	0.61 (0.49)	0.72 (0.45)
City per capita GDP (thousand yuan) †	42.51 (28.96)	33.87 (19.35)	44.15 (37.96)	43.25 (22.78)	48.08 (27.89)
Local geographic conditions					
Average elevation (km)	0.52 (0.64)	0.52 (0.62)	0.53 (0.66)	0.52 (0.62)	0.52 (0.65)
Standard deviation of elevation (km)	0.24 (0.19)	0.23 (0.19)	0.24 (0.20)	0.24 (0.18)	0.24 (0.19)
Average temperature (°C)	16.59 (4.39)	16.09 (4.28)	16.76 (4.29)	16.74 (4.46)	16.63 (4.52)
Total precipitation last year (mm)	1043.82 (537.54)	912.23 (352.91)	1047.94 (586.03)	1122.46 (591.60)	1055.08 (505.82)
Average wind speed last year (m/s)	1.98 (0.59)	1.94 (0.54)	1.99 (0.64)	1.94 (0.59)	2.05 (0.58)
Average sun duration last year (hour)	5.24 (1.22)	5.23 (1.16)	5.49 (1.09)	4.98 (1.27)	5.26 (1.30)
Average air pressure (hPa)	976.10 (54.95)	976.26 (54.27)	975.70 (55.31)	976.92 (53.55)	975.25 (57.25)
Number of observations	17,215	3547	5178	5192	3298

Note: Variables marked by † are deflated using the 2011 price. According to data from the World Bank, the official exchange rate of the Chinese Yuan to the US Dollar was 6.26 in 2011. Standard deviations are reported in parentheses.

The fast growth of wind power is also accompanied with high curtailment rates during our sample period with provincial disparity. A large body of literature has investigated the driving factors of the provincial variations. First, grid construction lagged far behind the rapid growth of wind power capacity due to coordination problems between grid companies and wind farms (Luo et al., 2016). Second, the current coal-dominant electricity system lacks flexibility to incorporate variable and intermittent wind power (Long et al., 2011; Lu et al., 2016; Pei et al., 2015). Finally, there exists a spatial mismatch between wind electricity supply and demand since majority of the wind capacity is concentrated in the "Three North Area"[13] and the load centre is located in the coastal provinces (Xia and Song, 2017a; Zhao et al., 2012). The transmission across provinces or regions faces two major obstacles: lack of physical transmission lines and province-based regulatory structure (Dong et al., 2018; Zhao et al., 2012).

In summary, the explanatory factors are more closely related to the electricity system and wind resources, and therefore can be considered uncorrelated with farmers' agricultural production decisions. Additionally, we incorporate control variables that may correlate with both power grid operations and agricultural production to strengthen the justification of exogeneity. These control variables account for local weather conditions, electricity demand associated with economic development, and the economic spillover effects of wind power development.

Our control variables include several time-variant characteristics from different sources. X_{jt} is a vector of village characteristics, including a binary variable for a village with a non-agricultural economy and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Z_{kt} is a vector of city characteristics, including per capita Gross Domestic Product (GDP) and weather variables (i.e., temperature, precipitation, wind speed, sunshine duration, and air pressure). The linear and quadratic terms of weather variables are included to control for their potential nonlinear effects. ϵ_{ijkt} is the error term, clustered in two dimensions: by feed-in tariff category within each province and by grid-year.

The time-variant control variables in Eq. (1) justify the exclusion restriction for our IVs in three ways. First, since 2013, China has implemented PPAP in poor counties (Zhang et al., 2020). Despite the limited grid-connected capacity of photovoltaic power generation during the initial stage of PPAP implementation (Li et al., 2023), which suggests that these projects are not closely related to our identification strategy relying on variations in power grid operations, we controlled for average sunshine duration and included household fixed effects to mitigate this issue.[14] Sunshine duration is a key factor influencing photovoltaic power generation and can also impact agricultural production (Zhang et al., 2017). The household fixed effects help control for variations in wealth levels, which may correlate with both the PPAP and agricultural production decisions.

Second, Eq. (1) includes weather conditions because they are simultaneously correlated with agricultural production decisions and the reliability of the electricity supply. On the one hand, since heat and water are direct inputs to agricultural production, weather shocks related to temperature and precipitation have been shown to affect labor input, planting area, and crop output (Deschênes and Greenstone, 2007; Aragón et al., 2021; Chen and Gong, 2021). Additionally, Zhang et al. (2017) suggests that other weather variables, such as wind speed, can also impact agricultural production. On the other hand, adverse weather conditions threaten power generation and grid operations. For example, wind power, which is the most volatile generation category, is determined mainly by the wind speed and air density. In addition to wind speed, high temperatures slightly decrease air density, leading to a reduction in power generation. In addition, extremely high or low temperatures may pose a threat to turbine components, thereby affecting turbine operation (Pryor and Barthelmie, 2013). Regarding power grid operation, extreme weather not only increases the frequency and intensity of peak load consumption, making it more difficult to balance electricity demand and supply (Auffhammer et al., 2017) but also affects the function of transmission lines. For example, extreme winds, lightning strikes, and flooding may cause transmission line failures (Ward, 2013). An increase in temperature can also decrease the capacity of fully loaded transmission lines (Schaeffer et al., 2012).

Third, the development of wind power interacts with local economic activities in several ways. More economically developed areas, which

[13] The "Three North Area" includes the Northeast, North and Northwest part of China.

[14] CLDS county codes have been randomized to protect the privacy of respondents. Therefore, we cannot know which counties in the sample have implemented PPAP.

typically have higher feed-in tariff rates and greater electricity demand, may be more susceptible to power outages. Additionally, wind farms can stimulate local economic activities. Previous studies have shown that the establishment of wind farms positively impacts the local economy by creating jobs, increasing personal income, generating tax revenue, and enhancing public goods (Brown et al., 2012; Xia and Song, 2017b). This development may also lead to changes in land use for non-agricultural purposes. Households are likely to take local economic conditions into account when making production decisions. Therefore, we control for village economic conditions (X_{jt}) and per capita GDP at the city level.

Based on the estimation in Eq. (1), we conduct three robustness checks. First, in line with the economic spillover effects of wind power development, we control for household labor endowments, given their potential correlation with these spillover effects and household agricultural production decisions. Since household labor endowments may change over time and are not fully captured by household fixed effects, we incorporate variations in household demographic structure, including household size and the composition of members by gender and age. Second, 1 % of households in our sample reported no access to electricity (Table 1). If this lack of access is a choice rather than a result of supply issues, these households do not belong to our target group. Therefore, we exclude households without electricity access as a robustness check. Third, we relax the panel restrictions to include all households, irrespective of the number of times they were observed during the sample period. We refer to this sample as the "*large sample*."[15] This approach allows us to test whether the sample selection used to construct the household panel biases our estimation. In this case, we replace household fixed effects with village fixed effects to account for local time-invariant conditions.

5. Results

5.1. Main results

Table 3 presents the first-stage regression results for our main estimation specified by Eq. (1) along with the three robustness checks. As expected, higher feed-in tariffs and wind curtailment rates are associated with reduced reliability of electricity supply. Additionally, for a given curtailment rate, higher mean elevation correlates with increased reliability, while greater variation in elevation is associated with reduced reliability of electricity supply.

Table 4 presents the impact of reliable electricity access on crop income and operating land area. Regarding the IV tests, the Kleibergen-Paap rk Wald F statistic is 39.65, which is much higher than the Stock-Yogo weak ID test critical value of 24.58 for a 10 % maximal IV size, thus rejecting the null hypothesis of weak IV. Additionally, the Hansen J statistic for each regression indicates that the effects identified by all of our IVs are not significantly different, consistent with the fact that all IVs measure the reliability of electricity supply resulting from intermittent wind power integration.

The IV estimates indicate that reliable electricity access significantly increases grain income (column (1)), but does not significantly affect income from cash crops (column (2)). Specifically, access to reliable electricity boosts grain income by 5303 yuan,[16] which corresponds to approximately 13.8 % of total household income in the sample. Correspondingly, we find that the irrigated farmland expands by 4.57 mu on average, equivalent to 1.4 time of the sample mean (column (3)), while the dryland or horticultural land do not have any significant impact. This may be explained by the fact that electricity is primarily used for irrigation in crop production. Although electrical equipment, such as drip and sprinkler irrigation systems, can enhance labor productivity, its application is more limited on land without existing irrigation facilities.

Table 3
First-stage regressions.

	Reliable electricity access (0/1)			
	Eq. (1)	RC1	RC2	RC3
	(1)	(2)	(3)	(4)
Feed-in tariff rate of wind power	−5.186***	−5.181***	−5.179***	−4.611***
	(1.805)	(1.795)	(1.859)	(1.594)
Wind curtailment rate	−0.017**	−0.017**	−0.017**	−0.016**
	(0.007)	(0.007)	(0.007)	(0.008)
Wind curtailment rate*Average elevation	0.012*	0.012*	0.012*	0.012*
	(0.007)	(0.007)	(0.007)	(0.007)
Wind curtailment rate*Standard deviation of elevation	−0.007	−0.008	−0.008	−0.006
	(0.016)	(0.016)	(0.016)	(0.015)
Observations	17,215	17,215	17,068	20,850
Control variables				
Village fixed effects	–	–	–	Yes
Household fixed effects	Yes	Yes	Yes	No
Grid-year fixed effects	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes
Household demographic structure	No	Yes	No	No

Notes: RC1, RC2, and RC3 denote the three robustness checks. Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

Next, we investigate the impact of reliable electricity access on labor-related inputs that may contribute to increased grain income. Table 5 presents the results. Our IVs successfully pass both the weak IV test and the overidentification test in each regression. We find that reliable electricity access has no significant effect on the number of agricultural laborers or tractor ownership. However, since the CLDS lacks information on time allocation and the use of agricultural machinery, we are unable to address time-based labor allocation and the substitution between labor and leased machinery, which limits our understanding of labor dynamics. To enhance our analysis, we examine the impact of reliable electricity access on income and consumption. If reliable electricity access leads to increased crop income without raising total household income, this may indicate a shift from non-farm to farm activities—an outcome that does not necessarily imply improved household welfare. Consistent with this hypothesis, we find that reliable electricity access does not affect total household income or essential household consumption.[17]

5.2. Mechanisms

We examine three mechanisms through which rural households can expand their irrigated farmland. First, since the late 1990s, China's rural land rental markets have gradually matured, providing farmers with an important way to acquire agricultural land (Kung, 2002; Deininger and Jin, 2005). However, frictions in non-agricultural labor markets can affect the allocation of productive factors (Yang, 2020). For instance,

[15] Descriptive statistics for the large sample are shown in Appendix Table 3.
[16] To show the robustness of this estimate against outliers, we either apply logarithmic transformations or trim various percentages of the top grain income values. The results are reported in Appendix Table 4.
[17] Essential household expenditures include food, housing costs, and transportation. We do not use total household consumption because other expenses are more likely to be partially covered by savings, which are influenced by long-term wealth rather than short-term income changes.

Table 4
Impact on crop income and operating land area.

	Income from Grain	Income from Cash Crops	Operating Area of Irrigated Farmland	Operating Area of Dry Farmland	Operating Area of Horticultural Land
	(1)	(2)	(3)	(4)	(5)
Reliable electricity access (0/1)	5302.709***	1405.164	4.568***	−1.133	0.849
	(1692.594)	(2283.059)	(1.349)	(2.188)	(0.651)
Observations	17,215	17,215	17,215	17,215	17,215
Control variables					
Household fixed effects	Yes	Yes	Yes	Yes	Yes
Grid-year fixed effects	Yes	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes	Yes
IV tests					
Kleibergen-Paap rk Wald F statistic	39.65	39.65	39.65	39.65	39.65
Hansen J statistic	2.117	4.199	2.796	4.144	2.496

Notes: Cash crops include fruits, vegetables, and other cash crops. Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

rural households may abandon some agricultural land as a safety net against unemployment in non-agricultural jobs. Since electrical equipment can reduce labor needs in agricultural production, rural households with reliable electricity access may be less likely to abandon land. Therefore, we investigate changes in the area of abandoned land as our second mechanism. Third, we examine the conversion of various types of agricultural land. In China, grassland and forestland are two other types of agricultural land classified at the same level as farmland and horticultural land.[18] We consider dry farmland, horticultural land, grassland, and forestland as a whole and explore the possibility of their conversion into irrigated farmland.

Table 6 presents the results regarding these mechanisms. Given that our IVs have passed both the weak IV test and the overidentification test in each regression, we find that reliable electricity access leads to a decrease in the abandoned area of irrigated farmland by 2.2 mu (column (2)). In contrast, reliable electricity access does not significantly affect the leasing of irrigated farmland (column (1)) or the use of other types of agricultural land (columns (3) and (4)). Taken together, our results suggest that reducing the abandoned area of irrigated farmland is the primary mechanism for expanding the scale of operations on irrigated farmland. While reducing abandonment occurs on a household's own land, leasing involves a transaction in the land rental market, which incurs transaction costs even in a developed market. Additionally, converting other agricultural land requires more effort than simply reducing the abandoned area of the same type of land. Consequently, the reduction in abandonment happens more quickly than through other mechanisms.

5.3. Robustness checks

In this section, we perform a wide range of meaningful robustness checks.[19] First, we control for household demographic composition to capture household labor endowments that may exhibit heterogeneous responses to local wind power development (referred as "*RC1*"). Second, we exclude households without electricity access, considering the possibility that they may choose not to be connected to the power grid (referred as "*RC2*"). Finally, in the main analysis to construct the household panel, we have excluded households observed only once during the sample period. In the third robustness check (referred to as "*RC3*"), we add these cross-sectional households and test whether the sample selection for constructing the household panel biases our estimation.

Table 7 presents the results of these robustness checks. To facilitate clearer comparison, we include not only the results of the three robustness checks but also the regression results from Eq. (1). For each outcome variable, the first column displays the regression result of Eq. (1), previously reported in earlier tables, while the second to fourth columns present the results of the robustness checks. In general, the

Table 5
Impact on input and household welfare.

	Number of Agricultural Labor	Own Tractor (0/1)	Total Income	Essential Household Expenditures
	(1)	(2)	(3)	(4)
Reliable electricity access (0/1)	0.883	−0.121	1686.029	2755.461
	(0.623)	(0.079)	(35,009.810)	(7860.892)
Observations	17,215	17,215	17,215	17,215
Control variables				
Household fixed effects	Yes	Yes	Yes	Yes
Grid-year fixed effects	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes
IV tests				
Kleibergen-Paap rk Wald F statistic	39.65	39.65	39.65	39.65
Hansen J statistic	0.937	4.020	3.648	0.773

Notes: Essential household expenditures include food, housing costs, and transportation. Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

[18] The classification can be found on the official website of the Ministry of Natural Resources at https://www.mnr.gov.cn/zt/hd/tdr/24tdr/tdbk/201106/t20110613_2050538.html.

[19] We also report the reduced-form regressions as a robustness check in Appendix Table 5. For each regression, at least one instrument significantly affects our outcome variables with the expected sign.

Table 6
Impact on land transfer and conversion.

	Leased Area of Irrigated Farmland	Abandoned Area of Irrigated Farmland	Leased Area of Other Agricultural Land	Abandoned Area of Other Agricultural Land
	(1)	(2)	(3)	(4)
Reliable electricity access (0/1)	0.545	−2.218**	0.009	−1.165
	(0.490)	(0.934)	(1.445)	(2.467)
Observations	17,215	17,215	17,215	17,215
Control variables				
Household fixed effects	Yes	Yes	Yes	Yes
Grid-year fixed effects	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes
IV tests				
Kleibergen-Paap rk Wald F statistic	39.65	39.65	39.65	39.65
Hansen J statistic	3.041	0.791	2.081	3.686

Notes: Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

results of the robustness checks align closely with our main findings. Although the magnitudes of the estimated impacts vary across samples, they remain comparable. Specifically, reliable electricity access significantly contributes to an increase in grain income by 5009 to 5303 yuan, an increase in the operating area of irrigated farmland by 4.39 to 4.60 mu, and a reduction in the abandoned area of irrigated farmland by 1.64 to 2.25 mu.

6. Conclusion

Using variations in the quality of household electricity access, our study investigates the impact of reliable electricity access on agricultural production, thus providing evidence of the potential benefits of rural electrification from a relatively underexplored perspective. We employ wind power feed-in tariffs, curtailment rates, the interaction between curtailment rates and a city's average elevation, and the interaction between curtailment rates and a city's standard deviation of elevation as IVs. This novel identification strategy addresses the endogeneity of electricity access while leveraging China's unique energy policy landscape. The results suggest that reliable electricity access reduces the area of irrigated farmland abandoned by rural households and increases the areas of irrigated farmland they operate, ultimately leading to greater grain income. By isolating the causal effect of reliable electricity, our study contributes to the growing body of evidence on the socioeconomic benefits of energy access, particularly in developing economies.

Our results provide several important policy implications for China and other developing countries where agriculture shifts toward dependence on electricity-powered machinery and faces challenges related to energy system reliability. First, the positive impact of reliable electricity access on agricultural production highlights the critical role of

Table 7
Robustness check for the increase in income and operating area.

	Income from Grain				Operating Area of Irrigated Farmland				Abandoned Area of Irrigated Farmland			
	Eq. (1)	RC1	RC2	RC3	Eq. (1)	RC1	RC2	RC3	Eq. (1)	RC1	RC2	RC3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Reliable electricity access (0/1)	5302.709***	5008.696***	5250.159***	5091.388*	4.568***	4.389***	4.601***	4.420***	−2.218**	−2.185**	−2.250**	−1.640*
	(1692.594)	(1670.192)	(1687.050)	(2598.305)	(1.349)	(1.274)	(1.362)	(1.104)	(0.934)	(0.930)	(0.942)	(0.953)
Observations	17,215	17,215	17,068	20,850	17,215	17,215	17,068	20,850	17,215	17,215	17,068	20,850
Control variables												
Village fixed effects	–	–	–	Yes	–	–	–	Yes	–	–	–	Yes
Household fixed effects	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Grid-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HH demographic structure	No	Yes	No	No	No	Yes	No	No	No	Yes	No	No
IV tests												
KP rk Wald F statistic	39.65	49.35	29.10	259.4	39.65	49.35	29.10	259.4	39.65	49.35	29.10	259.4
Hansen J statistic	2.117	2.177	2.103	2.126	2.796	2.725	2.780	1.891	0.791	1.104	0.972	2.145

Notes: RC1, RC2, and RC3 denote the three robustness checks. Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

electrification infrastructure in supporting rural development and sustainable intensification. This is especially relevant given the global shift toward agricultural mechanization and the increasing reliance on energy-intensive practices such as irrigation, cold storage, and digital farming (Mockshell and Birner, 2015; Belton et al., 2021). Policymakers can prioritize extending electricity coverage in rural areas—particularly in regions with high agricultural potential but inadequate grid services.[20] Targeted interventions, such as subsidies for energy-efficient equipment, training programs for modern farming techniques, and financial support for electricity-based production practices, can enhance the development gains from electrification.

Second, our identification strategy—leveraging the integration of wind power—illustrates the broader interplay between renewable energy development and rural electrification. This dual focus on decarbonization and development aligns with global priorities. However, as our findings indicate, the volatility of renewable energy can pose challenges for electricity reliability. This underscores the importance of complementary investments in grid flexibility, energy storage, and advanced management systems. While the Chinese context provides a unique setting with large-scale grid integration of renewables, the mechanisms we identify—linking electricity reliability to agricultural production—are relevant for many developing countries facing similar structural challenges. For instance, in South Asia, where agriculture is highly sensitive to irrigation and energy reliability remains a constraint, our study offers valuable insights on aligning energy policy with agricultural transformation goals.

Electricity reliability would ideally be assessed using high-frequency data on outage duration and severity for more granular samples. However, such data are currently unavailable in China and many developing countries. Information on reliable electricity access at the micro household level remain extremely limited. Future research that focuses on collecting data on outage duration and severity more frequently at the household level would facilitate more nuanced studies on the interactions between renewable energy integration and sustainable agricultural practices. Additionally, we acknowledge that our findings may not apply to countries with different agricultural practices or energy sector dynamics. Therefore, future research conducted in diverse settings is essential to assess the external validity of our findings and to gain a more comprehensive understanding of the causal impact of reliable electricity access on agricultural production.

CRediT authorship contribution statement

Fang Xia: Writing – original draft, Formal analysis, Data curation. **Xuwen Gao:** Methodology, Formal analysis, Data curation. **Shenggen Fan:** Validation, Conceptualization. **Feng Song:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

None.

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Appendix A. Appendix

Appendix Table 1
Feed-in tariff rates of wind power (Unit: Yuan).

	Year 2011	Year 2013	Year 2015	Year 2017
Category I	0.51	0.51	0.49	0.47
Category II	0.54	0.54	0.52	0.50
Category III	0.58	0.58	0.56	0.54
Category IV	0.61	0.61	0.61	0.60

Appendix Table 2
Wind curtailment rates (%).

	Year 2011	Year 2013	Year 2015	Year 2017
Anhui	0.00	0.00	0.00	0.00
Beijing	0.00	0.00	0.00	0.00
Chongqing	0.00	0.00	0.00	0.00
Fujian	0.00	0.00	0.00	0.00
Gansu	25.25	20.65	39.00	33.00
Guangdong	1.00	0.00	0.00	0.00
Guangxi	0.00	0.00	0.00	0.00
Guizhou	0.00	0.00	0.00	0.00
Hainan	0.00	0.00	0.00	0.00
Hebei	3.86	16.59	10.00	7.00
Heilongjiang	14.39	14.61	21.00	14.00
Henan	0.00	0.00	0.00	0.00
Hubei	0.00	0.00	0.00	0.00
Hunan	0.00	0.00	0.00	0.00
Inner Mongolia	23.10	16.00	18.00	15.00
Jiangsu	0.00	0.00	0.00	0.00

(continued on next page)

[20] While the rapid decline in solar panel costs has made them a competitive electricity source for rural households, off-grid solar power has proven to be an imperfect substitute for grid electricity (Lee et al., 2016). Households often prefer grid electricity, even at low levels of economic development (Burgess et al., 2020).

Appendix Table 2 (*continued*)

	Year 2011	Year 2013	Year 2015	Year 2017
Jiangxi	0.00	0.00	0.00	0.00
Jilin	21.02	21.79	32.00	21.00
Liaoning	10.45	5.00	10.00	8.00
Ningxia	0.00	0.73	13.00	5.00
Qinghai	0.00	0.00	0.00	0.00
Shaanxi	0.00	2.96	0.00	4.00
Shandong	1.17	0.00	0.00	0.00
Shanghai	0.00	0.00	0.00	0.00
Shanxi	0.00	0.00	2.00	6.00
Sichuan	0.00	0.00	0.00	0.00
Tianjin	0.00	1.68	0.00	0.00
Xinjiang	5.20	5.23	32.00	29.00
Yunnan	4.90	3.68	3.00	3.00
Zhejiang	0.00	0.00	0.00	0.00

Appendix Table 3

Descriptive statistics for the large sample.

	All waves	Wave 2012	Wave 2014	Wave 2016	Wave 2018
Electricity access					
No power outages last year (0/1)	0.20	0.12	0.18	0.22	0.27
	(0.40)	(0.32)	(0.39)	(0.41)	(0.44)
No electricity access last year (0/1)	0.01	0.00	0.01	0.01	0.01
	(0.08)	(0.07)	(0.08)	(0.09)	(0.08)
Outcomes related to agricultural production					
Engaged in agricultural production last year (0/1)	0.60	0.71	0.60	0.57	0.54
	(0.49)	(0.45)	(0.49)	(0.49)	(0.50)
Number of agricultural labor last year	1.09	1.36	1.10	1.01	0.94
	(1.21)	(1.66)	(1.08)	(1.05)	(1.04)
Had tractor last year (0/1)	0.87	0.86	0.88	0.87	0.89
	(0.33)	(0.35)	(0.33)	(0.34)	(0.32)
Operating area of irrigated farmland last year (mu)	1.37	1.46	1.44	1.30	1.28
	(3.32)	(3.78)	(3.33)	(3.02)	(3.21)
Operating area of dry farmland last year (mu)	2.07	2.42	1.92	2.06	1.96
	(4.86)	(4.93)	(4.40)	(5.30)	(4.72)
Operating area of horticultural land last year (mu)	0.20	0.16	0.18	0.21	0.26
	(1.95)	(1.20)	(1.54)	(2.20)	(2.60)
Operating area of grassland & forestland last year (mu)	0.73	1.02	0.79	0.52	0.65
	(9.68)	(15.74)	(11.01)	(3.82)	(3.78)
Leased area of irrigated farmland last year (mu)	0.12	0.16	0.13	0.10	0.09
	(1.65)	(2.80)	(1.64)	(0.86)	(0.78)
Leased area of dry farmland last year (mu)	0.30	0.21	0.29	0.37	0.27
	(3.51)	(1.75)	(4.24)	(4.09)	(2.57)
Leased area of horticultural land last year (mu)	0.01	0.01	0.01	0.01	0.03
	(0.61)	(0.25)	(0.22)	(0.20)	(1.29)
Leased area of grassland & forestland last year (mu)	0.06	0.01	0.14	0.04	0.02
	(5.74)	(0.27)	(10.21)	(2.54)	(0.47)
Abandoned area of irrigated farmland last year (mu)	0.54	0.34	0.61	0.57	0.62
	(1.66)	(1.23)	(1.80)	(1.69)	(1.76)
Abandoned area of dry farmland last year (mu)	0.74	0.37	0.73	0.92	0.84
	(4.27)	(1.85)	(4.71)	(5.27)	(3.57)
Abandoned area of horticultural land last year (mu)	0.06	0.07	0.06	0.07	0.05
	(0.89)	(1.11)	(0.89)	(0.93)	(0.47)
Abandoned area of grassland & forestland last year (mu)	0.31	0.50	0.20	0.33	0.25
	(4.67)	(9.11)	(1.76)	(3.05)	(2.41)
Income from grain (yuan) †	2518.5	2861.1	2544.3	2491.2	2164.9
	(5485.3)	(5213.1)	(5512.9)	(5709.7)	(5341.4)
Income from cash crops (yuan) †	871.6	984.4	799.9	887.6	837.8
	(6235.4)	(5257.0)	(6693.1)	(6256.6)	(6418.7)
Household characteristics					
Total income (yuan) †	38,329.0	26,678.0	42,274.5	38,843.7	43,669.5
	(91,627.5)	(59,064.2)	(113,386.5)	(67,827.3)	(111,526.7)
Essential household expenditures (yuan) †	11,526.2	9004.0	12,150.1	12,087.3	12,333.8
	(18,395.6)	(11,800.7)	(19,827.2)	(16,771.5)	(23,307.1)
Household size	2.97	3.12	3.05	2.92	2.76
	(1.55)	(1.49)	(1.58)	(1.56)	(1.56)
Share of female household members	0.50	0.49	0.51	0.50	0.50
	(0.25)	(0.23)	(0.24)	(0.25)	(0.27)
Share of children (0–15)	0.14	0.15	0.15	0.14	0.13
	(0.20)	(0.20)	(0.20)	(0.20)	(0.20)
Share of adults (16–60)	0.55	0.62	0.57	0.53	0.50
	(0.37)	(0.35)	(0.37)	(0.38)	(0.39)

(*continued on next page*)

Appendix Table 3 (*continued*)

	All waves	Wave 2012	Wave 2014	Wave 2016	Wave 2018
Share of old people (>60)	0.30	0.21	0.28	0.32	0.37
	(0.38)	(0.34)	(0.37)	(0.39)	(0.41)
Local economic conditions					
Village had non-agricultural economy last year (0/1)	0.26	0.33	0.21	0.26	0.25
	(0.44)	(0.47)	(0.41)	(0.44)	(0.43)
Share of village expenditure on infrastructure ranked among the top three last year (0/1)	0.60	0.59	0.53	0.61	0.71
	(0.49)	(0.49)	(0.50)	(0.49)	(0.45)
City per capita GDP (thousand yuan) †	43.89	33.86	46.59	44.40	49.41
	(30.89)	(19.12)	(41.43)	(23.90)	(29.31)
Local geographic conditions					
Average elevation (km)	0.50	0.51	0.51	0.50	0.50
	(0.63)	(0.61)	(0.65)	(0.61)	(0.64)
Standard deviation of elevation (km)	0.23	0.23	0.23	0.23	0.23
	(0.19)	(0.19)	(0.20)	(0.18)	(0.18)
Average temperature (°C)	16.62	16.02	16.86	16.75	16.68
	(4.47)	(4.40)	(4.33)	(4.54)	(4.60)
Total precipitation last year (mm)	1056.11	907.00	1076.47	1133.93	1059.56
	(548.88)	(355.05)	(608.79)	(597.73)	(508.36)
Average wind speed last year (m/s)	1.98	1.95	1.99	1.95	2.06
	(0.59)	(0.53)	(0.63)	(0.58)	(0.58)
Average sun duration last year (hour)	5.25	5.27	5.48	4.99	5.30
	(1.21)	(1.17)	(1.09)	(1.26)	(1.29)
Average air pressure (hPa)	977.63	977.97	977.35	978.26	976.73
	(53.91)	(53.18)	(54.24)	(52.63)	(56.07)
Number of observations	20,850	4246	6191	6334	4079

Note: One mu is 1/15 ha. Variables marked by † are deflated using the 2011 price. According to data from the World Bank, the official exchange rate of the Chinese Yuan to the US Dollar was 6.26 in 2011. Standard deviations are reported in parentheses.

Appendix Table 4
Robustness check for outliers.

	Log (Income from Grain + 1)	Inverse Hyperbolic Sine (Income from Grain)	Income from Grain (Top 1 % Trimmed)	Income from Grain (Top 2.5 % Trimmed)	Income from Grain (Top 5 % Trimmed)
	(1)	(2)	(3)	(4)	(5)
Reliable electricity access (0/1)	5.065**	5.474**	4636.122**	4568.882***	4027.415***
	(2.030)	(2.214)	(1962.297)	(1517.424)	(1068.363)
Observations	17,215	17,215	17,018	16,704	16,123
Control variables					
Household fixed effects	Yes	Yes	Yes	Yes	Yes
Grid-year fixed effects	Yes	Yes	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes	Yes	Yes
IV tests					
KP rk Wald F statistic	39.65	39.65	32.48	18.72	11.99
Hansen J statistic	1.867	1.877	1.848	1.656	1.695

Notes: Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

Appendix Table 5
Reduced-form regressions.

	Income from Grain	Operating Area of Irrigated Farmland	Abandoned Area of Irrigated Farmland
	(1)	(2)	(3)
Feed-in tariff rate of wind power	−16,825.765	−21.163**	11.750***
	(12,075.980)	(8.178)	(4.140)
Wind curtailment rate	−131.464***	−0.051**	0.035**
	(26.331)	(0.022)	(0.014)
Wind curtailment rate*Average elevation	39.712	0.113***	−0.029*
	(39.227)	(0.035)	(0.017)
Wind curtailment rate*Standard deviation of elevation	203.005	−0.285***	0.038
	(120.040)	(0.088)	(0.032)
Observations	17,215	17,215	17,215
Control variables			
Household fixed effects	Yes	Yes	Yes

(*continued on next page*)

Appendix Table 5 (*continued*)

	Income from Grain	Operating Area of Irrigated Farmland	Abandoned Area of Irrigated Farmland
	(1)	(2)	(3)
Grid-year fixed effects	Yes	Yes	Yes
Local weather controls	Yes	Yes	Yes
Local economic controls	Yes	Yes	Yes

Notes: Local weather controls include temperature, precipitation, wind speed, sunshine duration, and air pressure. We include both linear and quadratic terms of these weather variables. Local economic controls include city per capita GDP, a binary variable for a village with a non-agricultural economy, and a binary variable for infrastructure construction accounting for the top three village financial expenditures. Standard errors in parentheses are two-way clustered by feed-in tariff category within each province and by grid-year. *** significant at 1 %; ** significant at 5 %; * significant at 10 %.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108812.

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