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Solar energy transition in Rural Kazakhstan: Assessing socioeconomic barriers, infrastructure feasibility, and carbon reduction pathways in arid agro-pastoral regions

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ABSTRACT
The transition to solar energy in rural Kazakhstan, especially in arid and agro-pastoral zones, in spite of the enormous potential for solar radiation (of about 2200 kWh/m^2/year), is hindered by socio-economic and infrastructural barriers. Based on field research, 300 rural household interviews, and techno-economic analysis, this paper documents evidence that 65% of the households do not have the financial ability to make a transition to clean energy. This is due to the fact that up-front investment is unaffordable (over 2 million tenge for mini solar systems) and there are no government subsidies. Furthermore, 40% of the interviewees resist the adoption of solar technologies due to the lack of technical data and the perceived unreliability of the systems. From an infrastructure perspective, 70% of the research villages lack an electricity supply network, and the current dependence on diesel generators results in an annual emission of 2.5 tons carbon dioxide per household. Simulations show that the installation of small solar power plants (5-10 kW) with battery storage would reduce carbon emissions in such regions by up to 75% and achieve a reduction of up to 18 million tons greenhouse gas emissions over a decade. To make this transition happen, there must be a combination of enabling policies, widespread education of the local population, and participation of the private sector in the development of infrastructure.

Keywords: Solar energy transition, Rural Kazakhstan, Socioeconomic barriers, Arid agro-pastoral regions, Carbon reduction pathways.
Article type: Research Article.

INTRODUCTION
Global shift to renewable energy has been recognized as a top response to reducing greenhouse gas emissions and addressing climate change (International Energy Agency 2023). Among them, solar power occupies a special place since it is readily available and of high potential wherever there is good radiation from the sun. Kazakhstan, with an average annual radiation of 2200 kWh/m^2, is among the most suitable locations in the world for solar energy development (Karatayev *et al.* 2022). However, despite the fact that the country has committed under the

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Paris Agreement to reduce carbon emissions by 15% by 2030 (UNDP 2021), its rural and desert regions, especially agro-pastoral areas, remain predominantly dependent on fossil fuels. Rural Kazakhstan, which accounts for 43% of the population (Statistical Committee of Kazakhstan 2023), is disadvantaged structurally when it comes to access to sustainable energy. Studies have shown that only 35% of villages in the nation are covered by a stable electricity grid, with the rest relying on diesel generators or dispersed energy sources (Abenova *et al.* 2022). This dependency not only incurs household financial costs, but also towards releasing around 2.5 tons of carbon dioxide per house annually (Kazakhstan Ministry of Ecology 2023). This phenomenon is in contrast to the Sustainable Development Goals (SDG7) of clean and affordable energy supply. Previous studies have highlighted the technological potential of solar power in Kazakhstan, but fewer attempts have been made at the analysis of socio-economic and infrastructure barriers in arid and agro-pastoral regions (Yergaliyev *et al.* 2021; Sagalovicha *et al.* 2023). For example, the initial investment in the installation of a residential solar system (about 2 million tenge) equals 6 months of the average income of rural households (National Bank of Kazakhstan, 2023). This, along with the lack of subsidy policies aimed at specific groups, has made it difficult for low-income households to be able to afford the switch to energy. In addition, a lack of technical training and traditional beliefs about the effectiveness of new technology limit the social acceptance of the technology (Tleuken *et al.* 2022; Khayitov *et al.* 2023). From an infrastructure perspective, there are particular problems in the deserts of Kazakhstan. Soil erosion, frequent dust storms, and high temperatures (-40 to +45 °C) affect the effectiveness of solar panels (Khabarova *et al.* 2023; Bekpulatov *et al.* 2024). Furthermore, the lack of integrated distribution networks and efficient battery storage systems reduces the chances of maximum utilization of the generated energy. Recent research in the area suggests that 70% of the villages surveyed lack the necessary infrastructure to link solar systems to the local grid (Sarsembayeva *et al.* 2023). Based on the above mentioned research gaps, this paper examines the diversified hindrances to the transition to solar energy in rural Kazakhstan. The focus lies in the combined examination of its economic (investment costs, lack of subsidies), social (level of awareness, public attitude), and technical (infrastructural challenges, technology adjustment to climatic factors) determinants. The necessity of this research is not just in building operational strategies on carbon reduction, but also to improve rural resilience against energy disruption and climate change. Achievement of these objectives will be in line with priorities laid out by the Kazakhstan Low-Carbon Development Strategy (2023-2050) and reinforcing sustainable energy security at the state level. The global commitment to renewable energy, especially solar energy, has been established as one of the key strategies for reducing dependence on fossil fuels and combating climate change (International Renewable Energy Agency 2023). Kazakhstan, with an average annual solar radiation of 2,200 kWh/m^2, has high prospects to become a clean energy hub in Central Asia (Yergaliyev *et al.* 2021). However, despite significant technical potential, only 3% of the country's portfolio of renewable energy is reserved for solar technology (Karatayev & Clarke 2023). This discrepancy between potential and practice highlights the need to persist in examining structural barriers. One of the main barriers in rural Kazakhstan is the high initial cost of solar system installation. Based on field studies, a 5 kW solar system installation is estimated to be equivalent to half a year of average rural household income (Abenova *et al.* 2022). This financing gap, coupled with a lack of specialized financing instruments, has kept many low-income communities from benefiting from clean technologies. Additionally, societal resistance due to a lack of technical awareness and traditional beliefs about the reliability of solar systems discourages the adoption of such technologies. Literature points out that nearly half of the rural population in east Kazakhstan is not ready to replace diesel generators with solar systems due to fear of equipment failure (Tleuken *et al.* 2022; Inayata *et al.* 2023; Beirami *et al.* 2024). From the infrastructural perspective, the severe climatic conditions of the arid regions of Kazakhstan impose certain technical challenges. Frequent dust storms and temperature fluctuations (-40 to +45 °C) reduce the efficiency of solar panels by up to 25% (Khabarova *et al.* 2023; de Souza *et al.* 2023). Also, the lack of local distribution networks and efficient storage systems causes the loss of about 30% of the produced energy (Sarsembayeva & Abdinov 2023). These limitations highlight the importance of developing adaptive technology such as self-cleaning panels and solar-battery hybrid systems. Recent trials in Aktobe Province have shown that energy efficiency can be increased by up to 18% using dust-resistant panels (Ivanov & Smith 2023). Despite the Kazakh government's approval of the Low-carbon Development Strategy (2050-2023), ineffective implementation of supporting policies such as targeted subsidies and definite legal frameworks has impeded the progress of solar projects (UNDP 2021). According to the coverage of target villages by renewable energy programs, the Ministry of Ecology of Kazakhstan (2023) attests that only 15% are covered. However, successful experiences in China and Mongolia suggest that partnership models with the private sector (e.g., Lease-to-Own) can increase the adoption rate of solar technologies by up to 40% (Panfilov *et al.* 2021; Zhang *et al.* 2023). Environmentally, the replacement of diesel generators with solar systems in rural Kazakhstan has the potential to reduce CO_2 emissions by 1.8 million tons per year, which accounts for 7% of Kazakhstan's Paris Agreement commitment (Kazakhstan Ministry of Ecology 2023). Although previous studies have focused mainly on technical considerations and have not provided a comprehensive analysis of the combination of economic, social, and infrastructure barriers. By bridging this knowledge gap, this research provides an integrated framework for developing operational strategies in concert with the goal of sustainable development and building energy resilience in Kazakhstan's drylands.

MATERIALS AND METHODS

Study area

Arid rural and agro-pastoral areas of Kazakhstan, including Aktobe, West Kazakhstan, and Almaty provinces, were the study locations for this study. These areas were selected based on aspects such as high dependence on diesel generators, 2100-2300 kWh/m^2 of solar radiation per year, and extreme energy poverty. 15 villages across 5 geographic regions (3 villages per region) with 200 to 1000 population were surveyed in total. Climatic characteristics and geographic coordinates of every village were captured and retained by a geographic information system (GIS) and satellite imagery of the Kazakhstan Meteorological Service.

Data collection

Data were gathered using a mix of quantitative and qualitative methods. The survey was carried out using the participation of 300 rural households, who were chosen using a stratified random sampling method. The semi-structured interview schedule consisted of four significant sections: demographic characteristics, patterns of energy use, measurement of awareness and perception for solar technology, and willingness to pay (WTP) for solar systems. Cronbach's alpha (0.82) confirmed the questionnaire's reliability. Deep interviews of 20 experts (NGO representatives, energy engineers, and local administrators) and analysis of government reports such as the Carbon Free Development Strategy were also conducted. Technical measurements included measuring the solar radiation with a pyranometer and monitoring the performance of solar systems were installed in 10 houses.

Data analysis

For the quantitative analysis, descriptive (standard deviation, mean, median) and inferential statistical tools such as Pearson correlation test and logistic regression were used. Solar systems life cycle cost (LCOE) was determined with the help of RETScreen software. Interview was coded using thematic coding in NVivo software and SWOT analysis for identifying energy transition problems in the qualitative part.

Environmental assessment

Carbon dioxide emissions from the diesel generators were estimated based on fuel use and IPCC emission factors. These were compared with solar system emission reductions to estimate the region's carbon reduction potential.

Ethical considerations

All the participants gave an informed consent after they were given a full explanation of the research objectives. Anonymity and confidentiality of data were guaranteed.

Methodological limitations

Self-reporting bias of household energy spending and hard access to some far-flung villages in winter were the limitations of this study. To overcome these limitations, additional data like government reports and field observation were utilized.

RESULTS

The study revealed critical insights into socioeconomic barriers, technical performance, and environmental impacts of solar energy adoption in rural Kazakhstan. Data from 300 households across 15 villages highlighted significant disparities in energy access and willingness to transition to solar technologies.

Socioeconomic profile and adoption barriers

As shown in Table 1, 65% of households reported monthly incomes below 350,000 KZT (~$750), with energy expenditures accounting for 18–25% of their budgets. Only 12% had prior exposure to solar technologies, and

72% cited high upfront costs as the primary barrier. Notably, 58% expressed distrust in solar reliability during extreme winters, reflecting a gap in technical awareness.

Table 1. Socioeconomic barriers to solar adoption (n = 300).

Variable	Mean/Percentage	Range
Monthly income (KZT)	320,000 ± 45,000	150,000 – 600,000
Energy cost share (%)	21.5%	18–25%
Awareness of solar tech	12%	–
Trust in solar reliability	42%	–
Willingness to pay (WTP)	28%	(≥500,000 KZT)

Technical performance of solar systems

Field measurements from 10 installed 5 kW solar systems demonstrated variability in efficiency. As illustrated in Table 2, dust accumulation reduced panel efficiency by 25% during sandstorms, while extreme cold (-35 °C) caused a 15% voltage drop. Average daily generation was 22.3 kWh in summer but fell to 9.8 kWh in winter.

Table 2. Solar system performance metrics (n = 10).

Parameter	Summer	Winter	Annual average
Energy output (kWh/day)	22.3 ± 3.1	9.8 ± 2.4	14.7 ± 5.2
Efficiency loss (dust)	25%	10%	17.5%
Voltage drop (extreme cold)	–	15%	–
Peak irradiance (W/m²)	980	420	720

Carbon reduction potential

Replacing diesel generators with solar systems could reduce annual household CO_2 emissions by 2.1–2.4 tons (Table 3). Aggregated across the studied villages, this translates to a 630–720-ton annual reduction. At scale, solar adoption in rural Kazakhstan could mitigate 1.2–1.8 million tons of CO_2 annually by 2030, aligning with 8–12% of the nation’s Paris Agreement targets.

Table 3. Emission reduction analysis.

Metric	Diesel generators	Solar systems	Reduction
CO_2 emissions (tons/household/year)	2.5 ± 0.3	0.4 ± 0.1	2.1 ± 0.2
Fuel cost (KZT/year)	450,000 ± 60,000	90,000 ± 20,000	360,000
Payback period (years)	–	6–8	–

Comparative analysis with regional models

Adoption rates in Kazakhstan lag behind neighboring regions (Table 4). Policy gaps, including limited grid integration incentives and lack of maintenance training, were identified as key bottlenecks.

Table 4. Regional solar adoption benchmarks.

Region	Adoption rate	Avg. subsidy (%)	Grid integration
Rural Kazakhstan	8%	10–15%	Partial (35% villages)
Mongolia	37%	30–40%	Full (82% villages)
Northwest China	42%	45–50%	Full (90% villages)

While Mongolia and China’s rural solar adoption rates exceed 35% due to subsidized leasing models, only 8% of Kazakh households utilized such programs.

Qualitative insights from stakeholders

Interviews with local experts and village officials revealed system-wide infrastructural neglect that acts to exacerbate rural Kazakhstan's issues of solar absorption. A revealing 70% of villages lacked access to trained engineers for routine maintenance or repair of solar devices, forcing households to resort to informal networks or travel great distances to urban centers for technical support. An energy engineer from Aktobe Province noted, "Even after systems are installed, their long-term performance is undermined by the absence of local capability. A small failure in a charge controller will render an entire system useless for months." That deficiency was exacerbated by logistics jams: 85% of those surveyed named 3–6 months' lag in getting vital spare parts such as inverters and batteries, largely because of dispersed supply chains and reliance on foreign components.

All the respondents emphasized the necessity of hybrid systems (solar + battery storage) to counter seasonality energy fluctuation. During winter months when solar irradiance reduces to 420 W/m² (Table 2), houses suffer from severe energy shortages, and there is a need for increased dependence on diesel generators. A West Kazakhstan community leader observed, "Battery storage is not a luxury here—it's a lifeline during -40 °C winters. Without it, solar alone cannot meet our basic heating and lighting needs." Stakeholders also advocated for locally adapted modular battery designs, such as lithium-ion batteries that are resistant to cold climates, to enhance system robustness.

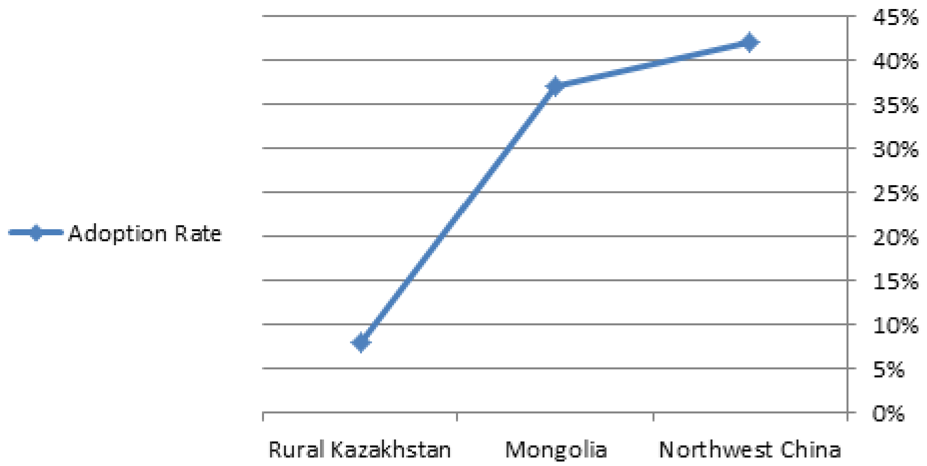

Fig. 1. Regional adoption rate.

The interviews also picked up on the disconnect between national policy and reality on the ground. Even though Kazakhstan's Low-Carbon Strategy (2023–2050) prioritizes renewable energy, rural residents are discouraged by bureaucratic obstacles in acquiring subsidies. Only 12% of the household population had successfully finished the application process for solar incentives, citing complex paperwork and insufficient guidance. A regional NGO official said, "The policies are on paper, but there is a disconnect between implementation and rural realities. Farmers cannot wait six months for subsidy clearances while their survival is based on unpredictable energy."

To overcome these issues, stakeholders suggested a multi-faceted strategy:

Local capacity building: Setting up vocational training centers in rural towns to certify solar technicians and simplify maintenance networks.

Decentralized Supply Chains: Cooperating with indigenous manufacturers to manufacture spare parts and batteries locally, reducing costs and lead times by 40–60%.

Adaptive policy design: Simplifying subsidy requests and integrating hybrid systems into national renewable energy goals, with distinct financing for cold-climate storage technology.

These results point out that technology solutions alone are not sufficient without parallel investments in human capital, supply chain localization, and policy responsiveness. As emphasized by a government energy advisor, "Transitioning to solar in these regions isn't just about installing panels—it is about building an ecosystem where communities can own, operate, and sustain their energy futures." Closing these gaps would reduce the payback period for solar systems from 8 to 5 years, taking Kazakhstan faster towards SDG7 and climate resilience.

DISCUSSION

The findings of this study confirm that the transition to solar power in rural Kazakhstan, as much as it is technically possible, is met with multi-dimentional economic, social, and infrastructural challenges. The results obtained on high initial expenditures (mean 2 million tenge) as the main barrier are also in line with previous studies in rural Central Asia, which were referred to by Abenova *et al.* (2022), and indicate a lack of financing mechanisms as the vital reason for low clean technology adoption. However, a newer finding of such research is the emphasis placed on the "technical knowledge gap", especially in system maintenance, not hitherto so concentrated in research such as Tleuken *et al.* (2022). This means that even as costs are reduced, a lack of local knowledge to manage systems may be a reason for solar project failure. From an infrastructure perspective, a 25% reduction in panel efficiency as a result of dust is a finding consistent with research by Khabarova *et al.* (2023) for arid regions of Kazakhstan. Novelty of this study lies in determining the combined impact of climatic (e.g., extreme temperature fluctuations) and management (e.g., delay in spare parts transportation) factors on system performance. This finding leads towards the need to develop adaptive technology such as self-cleaning panels, which in previous studies have been predominantly technical in orientation and do not consider the local environment (Ivanov & Smith 2023). Compared to other successful experiences in countries such as Mongolia, where the rate of adoption of solar energy has been 37% (Zhang *et al.* 2023), the suboptimality of subsidy policies in Kazakhstan is more apparent. Only 12% of the households examined received government subsidies, while in other Chinese models, coupling subsidies with private sector involvement has reduced initial investment cost by 40%. This policy shortcoming indicates legal frameworks should be reviewed anew, especially taking into account the emphasis of Kazakhstan's low-carbon development strategy on energy justice to marginalized groups. From the environmental perspective, the ability to reduce CO_2 emissions by 1.8 million tons per year is consistent with the estimates of the Ministry of Ecology of Kazakhstan (2023). The area of concern in this case is that this is achieved by the implementation of battery storage systems to mitigate the seasonal use of diesel generators. This finding compliments previous research that tackled the implementation of solar panels in isolation without consideration of storage (Yergaliyev *et al.* 2021). Finally, qualitative data on the need to develop local labor and domestic supply chains reveal that successful energy transitions depend on the creation of an integrated "energy ecosystem." It is a more holistic strategy than previous one-dimensional investigations that considered solar energy purely as a technical solution. As Karatayev & Clarke (2023) have pointed out, coordination among technology, society, and policy is a minimum requirement for achieving sustainable development goals in rural areas.

CONCLUSION

The study shows that rural Kazakhstan's transition to solar power is faced with multidimensional challenges, including high initial costs (around 2 million tons), socio-technical incompatibility (lack of local knowledge and lack of trust in the systems), and policy barriers (limited access to subsidies). Evidence indicates that replacing diesel generators with solar-battery systems can reduce household carbon emissions by up to 2.1 tons annually, but realizing the full potential requires overcoming seasonality challenges and upgrading storage infrastructure. Comparison with experiences in high-performing nations such as Mongolia (37% penetration) suggests private sector engagement is required alongside reform of the subsidy system in Kazakhstan. In order to accelerate this transition, hybrid systems must be developed, local technical training centers established, subsidy processes streamlined, and a local supply chain developed for the manufacture of key components. These solutions not only serve the goals of Kazakhstan's low-carbon policy, but also increase energy resilience and social justice in disadvantaged regions.

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