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Bridging the energy divide. China energy loans and rural electrification in developing countries

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ABSTRACT

This study investigates the impact of Chinese energy loans on rural electrification in 68 emerging countries from 2001 to 2023, addressing a critical gap in understanding the role of external financing in alleviating energy poverty. Using country fixed-effect and System Generalized Method of Moments (S-GMM) models, the findings provide robust evidence that a 1 % increase in Chinese energy loans leads to an average increase of approximately 0.10 percentage points in rural electricity access. However, corruption significantly attenuates this relationship, underscoring the importance of institutional quality in mediating the impact of infrastructure outcomes. Drawing on development economics theory, the analysis demonstrates that Chinese energy loans help address capital and infrastructural deficits in rural areas by facilitating the expansion of national grids, promoting off-grid renewable solutions, and supporting critical energy infrastructure. Illustrative examples, such as the Kafue Gorge Lower Hydropower Project in Zambia and the Karuma Hydropower Project in Uganda, underscore the transformative potential of such investments. The study offers novel empirical insights into how Chinese financing contributes to Sustainable Development Goal 7 (universal energy access). Policy implications suggest that while Chinese energy loans are effective in improving rural electrification, complementary reforms in governance and transparency are essential to maximise their developmental impact.

1. Introduction

Rural electrification remains one of the most pressing development challenges in emerging economies, with more than 600 million people worldwide—predominantly in Sub-Saharan Africa and South Asia—still lacking reliable access to electricity [1]. The absence of affordable and modern energy services not only perpetuates energy poverty but also constrains progress toward broader socio-economic outcomes, including education, health, and productivity [2]. Sustainable Development Goal 7 (SDG 7) underscores the global urgency of expanding access to "affordable, reliable, sustainable, and modern energy for all" by 2030, recognising energy access as a cornerstone for inclusive and sustainable development. Yet, rural areas continue to lag behind urban centres [3], reflecting persistent infrastructural deficits, weak institutional capacity, and uneven financing flows. Addressing these disparities is therefore essential if emerging countries are to achieve sustainable development in a balanced and equitable manner.

Against this backdrop, Chinese overseas energy financing has emerged as a critical source of infrastructure investment. Through state-owned banks and policy institutions, China has provided billions of dollars in loans for infrastructural development [4]. A significant portion of these loans is directed toward the energy sector, addressing critical gaps in electricity access, renewable energy adoption, and grid infrastructure in the emerging countries [4]. This focus stems from China's dual objectives of fostering economic partnerships and exporting its expertise in large-scale infrastructure development. Energy financing has become a key component of this strategy, with China providing loans to develop hydropower dams, coal-fired plants, solar farms, and transmission grids in energy-deficient regions [5].

These loans have enabled the completion of flagship projects such as the Karuma Hydropower Plant in Uganda and the Kafue Gorge Lower Hydropower Project in Zambia, both of which have expanded electricity supply in underserved regions. However, Chinese financing has also attracted critical scrutiny. Scholars and policymakers highlight concerns over opaque contractual terms, resource-backed collateralization, and the long-term debt sustainability risks for recipient countries [6,7]. Furthermore, empirical evidence on the distributional effects of Chinese

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Abbreviation

SDG – Sustainable Development Goals
GDP – Gross Domestic Product
FDI – Foreign Direct Investment
S-GMM – System Generalized Method of Moments
VIF – Variance Inflation Factor

energy loans remains limited, with most analyses focusing on national-level capacity expansion rather than rural access outcomes (Gallagher et al., 2018). This gap risks misleading policymakers into overestimating the inclusivity of Chinese financing, potentially leading to suboptimal strategies that prioritise large-scale generation without addressing rural energy poverty.

To address these gaps, this study investigates the role of Chinese energy loans in advancing rural electrification in emerging economies, with particular attention to the mediating role of governance. Specifically, it poses two central research questions.

1. What is the impact of Chinese energy loans on rural electrification rates across emerging countries?
2. How does the governance environment, particularly corruption levels, mediate the effectiveness of these loans in improving rural energy access?

These questions matter for both scholarly and policy debates. Empirically, they respond to the lack of cross-country, systematic evidence on the distributional outcomes of Chinese energy financing. Theoretically, they engage with development economics debates that balance infrastructure-led growth models with institutionalist perspectives emphasising governance quality. For policymakers, answering these questions is critical to avoid reliance on financing models that may expand supply without ensuring equitable distribution, especially for rural populations most at risk of being left behind.

The development economics theory offers a compelling framework for understanding the potential impact of Chinese energy loans on rural electrification. This theory posits that targeted investments in infrastructure play a critical role in fostering economic growth and reducing disparities between urban and rural areas [8]. In many emerging countries, rural regions suffer from chronic underinvestment in energy infrastructure, perpetuating cycles of poverty and limiting opportunities for growth [2]. Chinese energy loans address these gaps by providing the financial resources necessary for large-scale energy projects, such as hydropower dams, solar farms, and off-grid renewable solutions [9]. While these loans can contribute to reducing energy deficits and potentially stimulate economic activity, their outcomes are highly contextual. As political ecology and energy justice scholars argue, energy projects in the emerging countries often intersect with power asymmetries, land dispossession, and social inequalities, which may limit or unevenly distribute their developmental benefits [10].

Several motivations underpin this study. First, rural electrification remains a persistent challenge in emerging countries, particularly in Sub-Saharan Africa and South Asia, where millions of people lack access to reliable electricity [11]. Addressing this challenge is not only a technical necessity but also a moral imperative, as energy poverty disproportionately affects marginalised populations, exacerbating inequalities in education, health, and economic opportunities. Second, Chinese energy loans represent a unique financing model, often characterised by pragmatic approaches that prioritise infrastructural outputs over governance reforms [12,13]. Understanding the strengths and limitations of this model provides valuable insights into its effectiveness in addressing rural energy deficits. Third, the governance dynamics surrounding Chinese energy loans warrant closer examination. Corruption is likely to influence how effectively these loans translate into tangible benefits for rural populations [14].

The findings reveal a statistically significant and positive association between Chinese energy loans and rural electrification. Furthermore, the results show that corruption negatively moderates the relationship between Chinese energy loans and rural electrification, contrary to China's pragmatic approach to outward foreign direct investment (FDI), which often targets governance-challenged environments [13]. These findings underscore the importance of considering governance contexts in evaluating the effectiveness of development financing.

This paper makes three key contributions. First, it explicitly links Chinese energy loans to rural electrification outcomes, offering new evidence that moves beyond aggregate electrification metrics. Second, it integrates the role of corruption, showing how governance contexts shape the inclusiveness of external financing models. Third, this study integrates development economics theory into the analysis, offering a theoretical framework for understanding how external financing influences rural electrification. This integration bridges the gap between macroeconomic analyses of Chinese investments and micro-level studies on energy access, providing a more comprehensive understanding of the subject.

The findings underscore the transformative potential of targeted infrastructure investments, as posited by development economics theory, while also highlighting the challenges associated with governance and institutional quality. As emerging countries strive to achieve universal energy access and meet the objectives of SDG 7, this study offers valuable insights into how external financing can deliver sustainable and inclusive energy solutions. Additionally, prioritising renewable energy solutions can help align energy financing with global sustainability goals, including SDG 7, while reducing environmental trade-offs. By leveraging Chinese energy loans to expand access to clean and reliable energy, emerging countries can create a foundation for inclusive and sustainable development.

While SDG 7 is often equated with universal energy access (Target 7.1), our findings show that Chinese loans also facilitate progress toward interconnected sub-targets. First, we provide empirical evidence that loan-financed projects expand electricity access in rural areas, directly advancing Target 7.1. Second, the increasing share of Chinese-funded renewable energy projects—including hydropower, solar, and wind—contributes to Target 7.2, which aims to raise the global share of renewables. Third, projects that improve transmission and distribution networks indirectly enhance energy efficiency, thereby linking to Target 7.3. Finally, by positioning Chinese financing as a major instrument of South–South cooperation, the study underscores its role in advancing Target 7.a, which calls for strengthened international collaboration on energy access and technology transfer. By systematically aligning our findings with these SDG 7 sub-targets, this paper not only contributes to debates on external financing and rural electrification but also situates Chinese energy loans within the broader global development agenda.

The remainder of the paper is as follows. The theory and literature review are presented in the next section, while Section 3 contains the research methodology. Section 4 contains the results and discussions of the findings, and the paper concludes in Section 5 with policy implications, limitations and suggestions for future research.

2. Theory and literature review

2.1. Theoretical perspective

Rural electrification remains one of the most pressing development challenges in emerging countries, where large populations still lack access to affordable and reliable energy [1]. This study draws on insights from development economics to provide a conceptual foundation for examining how external financing, particularly Chinese energy loans, can alleviate energy poverty while recognising the importance of governance quality in shaping outcomes.

Development economics encompasses a wide range of theories that offer different perspectives on how economies grow and overcome structural constraints. The Linear Stages of Growth Model Rostow, 1990 [8] has traditionally emphasised the role of large-scale investments in infrastructure as catalysts for economic transformation. In rural areas, where governments and private investors are often reluctant to deploy capital due to perceived low returns, external financing fills an essential gap [15]. Development economics theory emphasises the importance of external capital flows in accelerating structural transformation, particularly in regions that lack the fiscal and technical capacity to invest in critical infrastructure Rostow, 1990[8]. While this framework highlights the importance of capital accumulation and aligns with the role of energy loans in bridging infrastructure deficits, it has been widely critiqued for its assumption of a uniform development trajectory across all economies and its limited consideration of institutional and governance factors.

To address these limitations, this study also incorporates elements of dependency theory and institutional economics. Dependency theory argues that external capital flows, particularly loans, can create new forms of dependency if not managed sustainably [16]. This perspective is especially relevant given concerns that Chinese loans may lock recipient countries into long-term debt obligations or exacerbate resource dependency. In parallel, institutional economics [17] underscores the importance of governance quality and institutional arrangements in shaping the effectiveness of external financing. Strong institutions can channel resources towards productive uses, while corruption or weak governance can dilute their developmental impact.

By combining insights from these theories, this study conceptualises Chinese energy loans as both an opportunity and a potential risk. On one hand, they align with Rostow's emphasis on targeted infrastructure investments as engines of rural development. On the other hand, dependency theory cautions against overreliance on external resources, while institutional economics emphasises the mediating role of governance quality—particularly corruption—in determining whether such loans lead to sustainable rural electrification. This integrative theoretical framing provides a nuanced lens through which to evaluate the transformative but context-dependent impact of Chinese energy loans on rural energy access.

2.2. Empirical literature review

Rural electrification is formally defined by the International Energy Agency [1] as the share of rural populations with access to reliable and affordable electricity, encompassing both on-grid and off-grid solutions. It is widely recognised as a cornerstone of socio-economic development, enabling improvements in education, healthcare, and productivity (Alegre-Bravo & Anderson, 2023). However, rural electrification rates remain persistently low in many emerging economies, particularly in Sub-Saharan Africa and South Asia. Chinese energy loans, for the purposes of this study, are defined as government-backed concessional or commercial loans provided by Chinese state-owned banks and policy institutions, such as the Export-Import Bank of China and the China Development Bank, specifically earmarked for energy sector projects abroad [18]. These include financing for generation (hydropower, coal, solar, wind), transmission, and distribution infrastructure.

A robust body of research has examined the macroeconomic effects of Chinese financing in recipient countries. Cheng and Qi (2021) demonstrate consistent positive correlations between Chinese investments and GDP growth, particularly in economies with limited infrastructure. Gallagher et al. (2018) provide compelling evidence that Chinese financing has helped bridge critical infrastructure gaps in sub-Saharan Africa, with estimated growth elasticities of 0.2–0.3 for energy sector investments. However, these macroeconomic analyses typically employ country-level aggregates that obscure distributional impacts, particularly the rural-urban divide in energy access. Chen et al. [18] note this limitation, finding that while Chinese projects increase national electrification rates, their subnational distributional effects remain understudied.

The energy sector has received particular attention, given its prominence in China's overseas portfolio. Chen et al. [18] document that 42 % of China's overseas energy financing between 2000 and 2018 targeted power generation projects, with hydropower representing the largest share. Recent work by Wen et al. [5] reveals an accelerating shift toward renewable energy projects, particularly in solar and wind energy, although fossil fuel investments remain substantial [18]. Aluko et al. [19] report that Chinese energy investments increase urban electrification rates 1.8 times faster than rural rates in their sample of 15 African countries. Byaro and Mmbaga [20] similarly document an urban bias in electrification outcomes, though they note exceptions where dedicated rural energy programs exist.

These studies importantly establish China's growing dominance in global energy finance, accounting for approximately 28 % of all cross-border power plant investments in emerging countries by 2020 [4]. Yet they predominantly analyse national-level capacity additions rather than actual electricity access outcomes, especially in rural areas. These studies suggest that without explicit targeting mechanisms, Chinese energy financing may inadvertently exacerbate rural-urban disparities in energy access, despite increasing aggregate supply. As Alegre-Bravo and Anderson (2023) note, this constitutes a critical oversight given that rural populations represent over 80 % of the global energy-poor.

External monies, such as Chinese energy loans, enable the development of energy systems that would otherwise remain underfunded, including extending grid connections, establishing off-grid renewable solutions, and constructing large-scale energy projects. For instance, Chinese-backed projects such as the Karuma Hydropower Plant in Uganda and the Kafue Gorge Lower Hydropower Project in Zambia have improved energy access in rural areas, creating opportunities for economic growth and improving quality of life [21]; [22,23]. By financing infrastructure that directly addresses energy poverty, these loans align with the broader goals of development economics theory, which emphasises the interplay between energy access, productivity, and societal well-being.

However, the relevance of external monies to rural electrification is not without contention. Critics argue that external financing may exacerbate dependency on foreign capital, fostering vulnerabilities in recipient countries [24]. The dependency theory warns of the potential long-term economic risks associated with external loans, particularly when tied to resource-backed agreements [7,25]. Such arrangements may compel recipient countries to overexploit their natural resources to meet repayment obligations, undermining sustainability and creating fiscal vulnerabilities [26]. Moreover, the heavy reliance on external funding may also disincentivise domestic resource mobilisation and private sector participation in the energy sector. Critics of external financing argue that long-term development requires building local capacity and fostering self-reliance rather than depending on foreign loans [27]. Without complementary policies to strengthen governance, enhance technical expertise, and mobilise domestic resources, the transformative potential of external financing for rural electrification may be limited.

Despite these critiques, Chinese energy loans offer a unique approach to addressing rural electrification challenges in emerging countries. Unlike traditional development financing, which often comes with stringent governance and reform conditions, Chinese loans emphasise infrastructural outputs and pragmatic implementation [13]. While this approach is questionable based on debt-trap theories [6,7], it has allowed Chinese lenders to finance large-scale energy projects in governance-challenged environments where other international financiers might hesitate to engage (Gallagher et al., 2018). For instance, the Garissa Solar Plant in Kenya, funded through Chinese loans, has provided off-grid solar solutions to rural populations, reducing reliance on biomass fuels and improving access to clean energy [21].

One of the distinguishing features of Chinese energy loans is their

ability to target critical infrastructural gaps in countries with limited access to alternative sources of financing [18]. In many parts of Sub-Saharan Africa and Southeast Asia, where rural electrification rates remain alarmingly low, Chinese lenders have stepped in to fill the void left by multilateral banks and private investors. By offering concessional loans and technology transfer, China has facilitated the development of energy infrastructure that directly benefits rural populations [28]. This aligns with the development economics theory's emphasis on external financing as a catalyst for growth in underdeveloped regions.

The pragmatic nature of Chinese financing is also evident in its focus on high-impact projects that address immediate needs [29]. Unlike conventional aid programs, which often involve lengthy approval processes and conditionalities, Chinese loans prioritise rapid implementation and tangible outcomes [6]. This approach has proven effective in expanding rural electrification in countries with significant energy poverty.

2.3. Corruption, China energy loans and rural electrification

Corruption plays a pivotal role in shaping the relationship between Chinese energy loans and rural electrification, often creating a paradoxical dynamic that both impedes and, in some cases, enhances the outcomes of such financing [13]. The governance context within which Chinese energy loans are deployed significantly influences their effectiveness, with corruption acting as a double-edged sword. On the one hand, corruption undermines the efficiency and sustainability of rural electrification projects by inflating costs, diverting funds, and compromising infrastructure quality [30]; [31]. On the other hand, it can sometimes expedite project implementation by bypassing bureaucratic bottlenecks, albeit at the expense of long-term governance and accountability [32].

The detrimental impact of corruption on the benefits of Chinese energy loans is particularly evident in cases where governance challenges are severe. In many emerging countries, where institutional capacity is weak, corruption often manifests in the form of inflated procurement contracts, kickbacks, and embezzlement [31]. Such practices siphon off funds intended for energy projects, reducing their effectiveness and delaying completion. Angola provides a compelling example of this dynamic. While Chinese loans have facilitated large-scale energy projects, such as the Lauca Hydropower Plant, widespread corruption within Angola's governance structures has marred their execution. Funds were reportedly misallocated through inflated contracts, and unauthorised payments were made to intermediaries, diverting resources away from project implementation [33]. These inefficiencies not only increased costs but also hindered the timely delivery of electricity to rural communities, thereby limiting the transformative potential of Chinese financing.

Corruption also affects the quality of infrastructure developed through Chinese energy loans. In environments where oversight is weak, the misappropriation of funds often leads to cost-cutting measures during the construction phase, resulting in substandard materials and technologies being used [34]. This is particularly problematic for rural electrification projects, where sustainability and durability are critical. For example, in Nigeria, Chinese-funded rural electrification initiatives faced significant criticism for employing low-quality equipment and inadequate maintenance practices, rendering some projects ineffective [35]. These shortcomings highlight how corruption can erode the long-term utility of energy infrastructure, undermining its ability to provide reliable electricity access to underserved populations.

However, the role of corruption is not exclusively negative. In certain contexts, it has paradoxically facilitated the implementation of rural electrification projects by bypassing bureaucratic inefficiencies and regulatory delays. Yung et al. [36] suggest that in countries with cumbersome governance structures, where lengthy approval processes often stall infrastructure development, informal arrangements enabled by corruption can expedite project timelines. This dynamic is particularly relevant in the context of Chinese energy loans, which prioritise rapid infrastructure delivery. For instance, in countries like the Democratic Republic of Congo, where governance frameworks are notoriously weak, Chinese-funded energy projects have been implemented more swiftly than similar initiatives financed by multilateral institutions [37]. By circumventing bureaucratic hurdles, corruption-enabled arrangements can sometimes ensure that rural electrification projects are completed within shorter timeframes, delivering immediate benefits to communities in need.

The willingness of Chinese lenders to engage in high-corruption environments further amplifies this effect McKinsey & Company ([38]. Unlike traditional development financiers, who often impose strict governance and transparency requirements as preconditions for funding, Chinese lenders adopt a more pragmatic approach that emphasises infrastructure outputs over procedural reforms (Gallagher et al., 2018). This approach has enabled Chinese energy loans to reach countries that are otherwise excluded from global financing networks due to their governance challenges. In Angola and Sudan, for example, Chinese-funded rural electrification projects have expanded electricity access to remote areas despite pervasive corruption [39]. While this strategy delivers immediate gains, it raises concerns about the long-term sustainability of these projects, particularly if governance issues remain unaddressed.

Comparison among prior studies is presented in Appendix A.

3. Research methodology

3.1. Data sampling

We began our sampling by identifying countries listed in the *China Loans Database* compiled by the Boston University Global Development Policy Centre. The choice of the 2000–2023 study period is informed by both data availability and substantive considerations. The *China Loans Database* provides consistent coverage beginning in 2000, which coincides with the launch of China's "Going Out" strategy and the acceleration of outward energy financing (Gallagher et al., 2018). This period also encompasses the Belt and Road Initiative, further intensifying China's overseas lending. The endpoint of 2023 ensures inclusion of the most recent records while accommodating lags between loan disbursement, project completion, and measurable electrification outcomes.

Countries with missing or incomplete data on key variables, particularly rural electrification, were removed to preserve consistency and reliability in the regression models. After applying these criteria, the final balanced sample comprised 68 emerging countries that received Chinese loans in the energy sector. Appendix B provides the full list of sample countries. Fig. 1 shows the sample countries on the global map.

3.2. Variable description and measurement

Dependent variable: The dependent variable in this study is rural electricity access, measured as the percentage of the rural population with access to electricity. This definition is consistent with the International Energy Agency [1] and the World Bank's World Development Indicators, which conceptualise rural electrification as reliable and affordable access to electricity for households outside urban areas. Rural electrification is a widely used metric in the energy access literature (Alegre-Bravo & Anderson, 2023).

Independent variable: The key independent variable is Chinese energy loans, measured in natural logarithms and as a percentage of Gross Domestic Product to address skewness. These loans are sourced from the China Africa Research Initiative database, which compiles official records of loan commitments by Chinese policy banks for energy-related infrastructure projects abroad. Following Chen et al. [18] and Dreher et al. [6], these loans are defined as government-backed concessional or commercial financing provided specifically for energy sector projects, including generation, transmission, and distribution

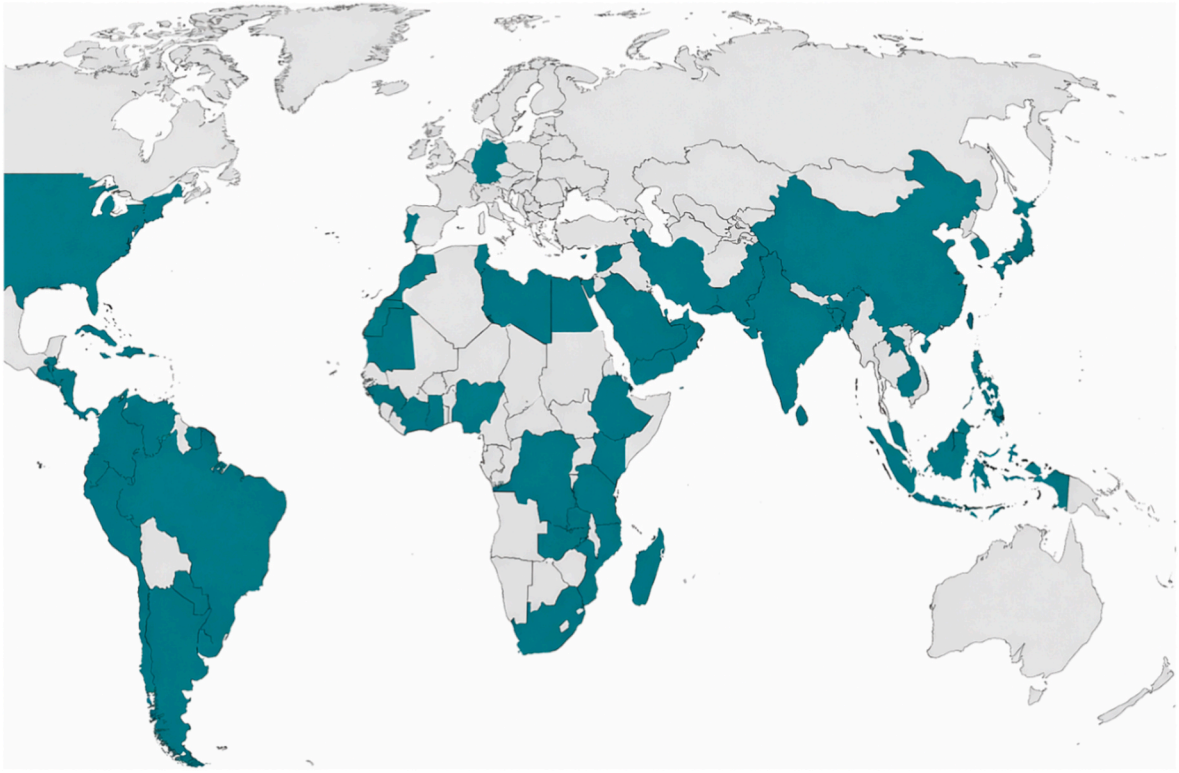

Fig. 1. Map chart of sample countries.

infrastructure. The percentage format is used for baseline regression, while the natural logarithm is for robustness.

Control variables were included based on theoretical and empirical justifications:

Economic development: GDP per capita (constant USD) is used as a proxy for economic development. Although this measure is widely adopted in development economics [5,19], we acknowledge its limitations, including its inability to capture distributional aspects and non-monetary dimensions of development [40]. Nonetheless, GDP per capita remains a standard and robust indicator for cross-country studies of electrification [18,19].

Rural population: The rural population share (% of total) is included to control for demographic pressures influencing electrification. This approach is consistent with studies highlighting the challenges of extending grid services to dispersed rural populations [1].

Foreign direct investment (FDI): Net FDI inflows (% of GDP) are included as an indicator of external capital availability. While FDI may complement infrastructure development, prior research [19,41] suggests its benefits are often urban-biased, making it important to control for when analysing rural outcomes.

Domestic credit: Domestic credit to the private sector (% of GDP) is included as a proxy for financial sector development and access to domestic capital. Greater credit availability can facilitate investment in infrastructure and expand household capacity to finance electricity connections. Byaro and Mmbaga [20] find that domestic credit is a significant determinant of electricity access in Sub-Saharan Africa, as deeper financial systems enable both public and private actors to invest in energy infrastructure. Controlling for domestic credit therefore helps isolate the specific influence of Chinese loans by accounting for domestic financial capacity that may independently promote rural electrification.

Food production index: The food production index (2014–2016 = 100) is included as a measure of agricultural productivity and rural economic vitality. Byaro and Mmbaga [20] highlight that higher agricultural output generates stronger electricity demand in rural areas, enhancing the economic feasibility of extending energy infrastructure. Improvements in food production also indicate better rural incomes and institutional support systems, which can indirectly foster energy access. Including this variable helps control for the role of agricultural development in shaping rural electrification outcomes, ensuring that the estimated effects of Chinese energy loans are not confounded by structural progress in the agrarian economy.

Corruption: Governance quality is captured using the Worldwide Governance Indicators corruption control index. This is justified by evidence from Isaksson and Kotsadam [42], who demonstrate how corruption mediates the effectiveness of foreign aid and investment in Africa. For easy interpretation, we follow prior studies [43]; [28,44] to use the reverse format, where high values indicate high corruption, in the empirical analysis.

All variables and data sources are summarised in Table 1 (Variable Description and Sources).

3.3. Econometric model

Our econometric framework is grounded in development economics theory, which emphasises the role of external capital in addressing structural constraints in developing economies. According to Rostow's (1960) *Linear Stages of Growth Model* and later extensions by Solow [45] and Romer [46] capital accumulation—particularly in infrastructure—drives economic transformation and social progress. In this context, Chinese energy loans serve as critical external capital inputs that help overcome rural infrastructure deficits, with their effectiveness conditioned by institutional quality and absorptive capacity. To empirically capture these relationships, the study models rural electrification as a function of Chinese energy loans (logged) and a set of control variables, including economic development (GDP per capita), economic growth, foreign direct investment, trade openness, domestic credit, and rural population.

The baseline specification adopts a country fixed-effects (FE) estimator, which accounts for unobserved heterogeneity across countries—such as institutional, geographic, or cultural factors—that may

Table 1
Variable description and sources.

Variable name	Description	Source
Dependent variable		
Rural electrification	Rural electrification is the percentage of the rural population with access to electricity.	World Development Indicators
Independent variables		
China energy loans	Total amount of China loans towards the energy sector of the recipient country, measured in US$ millions. It is measured as a percentage of GDP for baseline regression and a natural log transform for robustness. These measurements are derived from energy loans in millions.	Boston University Global Development Policy Centre
Other independent variable		
Corruption	Control of Corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. Estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution, i.e. ranging from approximately −2.5 to 2.5. For easy interpretation, we use the reverse format where high values indicate high corruption	World Governance Indicators
Control variables		
Foreign direct investment	Foreign direct investment are the net inflows of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor. It is the sum of equity capital, reinvestment of earnings, other long-term capital, and short-term capital as shown in the balance of payments. This series shows net inflows (new investment inflows less disinvestment) in the reporting economy from foreign investors, and is divided by GDP.	World Development Indicators
Economic development	GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in current U.S. dollars.	World Development Indicators
Rural population	Rural population refers to people living in rural areas as defined by national statistical offices. It is calculated as the difference between total population and urban population.	World Development Indicators
Food production index	Food production index covers food crops that are considered edible and that contain nutrients. Coffee and tea are excluded because, although edible, they have no nutritive value.	World Development Indicators
Domestic credit	Domestic credit to private sector refers to financial resources provided to the private sector by financial corporations, such as through loans, purchases of nonequity securities, and trade credits and other accounts receivable, that establish a claim for repayment. This indicator is expressed as a percentage of Gross Domestic Product (GDP) which is the total income earned through the production of goods and services in an economic territory during an accounting period.	World Development Indicators

influence both loan allocation and electrification outcomes. The fixed-effects model is preferred over pooled regression because it controls for time-invariant country-specific effects, reducing omitted-variable bias [47]; [48]. Robust standard errors are clustered at the country level to correct for serial correlation and heteroskedasticity within panels. Year dummies are also included to capture global shocks and temporal trends in energy financing.

We specify our model as follows:

$$\begin{aligned} &Rural\ electrification_{it} = a + \beta_1 China\ energy\ loans_{it} \\ &+ \beta_2 Economic\ development_{it} + \beta_3 Foreign\ direct\ investment_{it} \\ &+ \beta_4 Rural\ population_{it} \\ &+ \beta_5 Food\ production\ index_{it} + \beta_6 Domestic\ credit_{it} + \varepsilon_{it} \ldots\ldots EQ1 \end{aligned}$$

See Table 1 for variable description and sources.

A crucial innovation in this study is the inclusion of an interaction term between energy loans and corruption levels, which operationalises our theoretical expectation from infrastructure financing theory that institutional quality mediates the effectiveness of external financing. This specification allows us to test whether Chinese loans have differential impacts across governance contexts while maintaining the model's transparency.

We specify equation (2) as follows

$$\begin{aligned} &Rural\ electrification_{it} = a + \beta_1 China\ energy\ loans_{it} + \beta_2 Corruption_{it} \\ &+ \beta_3 China\ energy\ loans^{*} Corruption_{it} + \beta_4 Economic\ development_{it} \\ &+ \beta_5 Foreign\ direct\ investment_{it} + \beta_6 Rural\ population_{it} \\ &+ \beta_7 Food\ production\ index_{it} + \beta_8 Domestic\ credit_{it} + \varepsilon_{it} \ldots\ldots EQ2 \end{aligned}$$

3.4. Other identification strategy – S-GMM

To rigorously address endogeneity concerns, we complement our baseline pooled and fixed effect regression with the System Generalized Method of Moments (S-GMM), following the established methodology of Arellano and Bond (1991) and Blundell and Bond (1998). Although S-GMM is most efficient in panels with large cross-sections (N) and relatively short time periods (T), our dataset of 68 countries over 22 years still meets conditions under which GMM estimation is warranted. This dynamic panel estimator is particularly well-suited for our analysis, as it effectively addresses several econometric challenges inherent in studying the relationship between energy loans and rural electrification.

First, rural electrification is inherently dynamic, as past access strongly influences current levels. Including a lagged dependent variable risks Nickell bias in fixed-effects estimators, which S-GMM corrects through internal instrumentation. Unlike static models or alternative dynamic estimators like Pooled Mean Group or Cross-Sectionally Augmented ARDL, which require either strict cross-sectional

independence (Pesaran, 2006) or long time-series data (Chudik and Pesaran, 2015), S-GMM performs well with our moderately sized panel of 24 countries over 21 years. This makes it particularly suitable given the irregular timing of Chinese loan disbursements across countries.

Second, Chinese energy loans may be endogenous due to reverse causality—countries with electrification deficits are more likely to receive loans—and omitted variables such as bilateral political relations. S-GMM mitigates this by using lagged levels and differences as instruments, reducing simultaneity bias.

Third, adopting S-GMM ensures comparability with prior studies on Chinese finance and governance (e.g., Ref. [13,49]), which confront similar challenges. Diagnostic tests (Hansen and Arellano-Bond) confirm the validity of the instrument and the absence of serial correlation, supporting the reliability of the estimator. We specify the S-GMM model as follows:

$$Rural\ electrification_{it} = a + \beta_1 InChina\ energy\ loans_{it} + \beta_2 Rural\ electrification_{i,t-1} + \beta_3 Economic\ development_{it} + \beta_4 Foreign\ direct\ investment_{it} + \beta_5 Rural\ population_{it} + \beta_6 Food\ production\ index_{it} + \beta_7 Domestic\ credit_{it} + \mu i + \gamma t + \varepsilon \ldots\ldots EQ3$$

$$Rural\ electrification_{it} = a + \beta_1 InChina\ energy\ loans_{it} + \beta_2 Corruption_{it} + \beta_3 China\ energy\ loans{*}Corruption_{it} + \beta_4 Rural\ electrification_{i,t-1} + \beta_5 Economic\ development_{it} + \beta_6 Foreign\ direct\ investment_{it} + \beta_7 Rural\ population_{it} + \beta_8 Food\ production\ index_{it} + \beta_9 Domestic\ credit_{it} + \mu i + \gamma t + \varepsilon_{it} \ldots\ldots EQ4$$

The endogenous variable is China's energy loans and is instrumented by the one-year lag of independent variables

Our implementation of S-GMM adheres to best practices outlined in Roodman (2009), including the use of a collapsed instrument matrix to prevent overfitting and the application of Windmeijer's (2005) two-step estimator with standard error correction to account for heteroskedasticity. The validity of our GMM approach rests on two key assumptions: first, that the error terms exhibit no second-order serial correlation (AR(2)), and second, that the instruments are exogenous, as verified through Hansen tests (Baum et al., 2003). Our results, presented in Table 4 (columns 4 & 7), confirm that these conditions are met, with AR(2) p-values >0.1 and Hansen test p-values >0.7, supporting the model's specification.

4. Results

4.1. Descriptive statistics

Table 2 provides a summary of the descriptive statistics for the key variables used in the analysis. The mean value of Chinese energy loans (in US$ millions), at $881.2 million (5.63 % of GDP), reflects significant financial flows into the energy sectors of recipient countries. However, the high standard deviation of $2187 million indicates considerable variability in loan sizes, suggesting that some countries receive disproportionately larger amounts than others. This disparity highlights the importance of examining how loan allocation affects rural electrification outcomes across various contexts. The mean level of rural electrification, at 61.59 %, indicates substantial progress in energy access but also highlights persistent gaps, particularly in the lower quartile, where only 21.90 % of rural populations have access to electricity. The median value of 79.30 % shows that half of the sampled countries are closer to achieving higher electrification rates. At the same time, the spread between the 25th and 75th percentiles suggest varying degrees of success in addressing rural energy poverty.

Foreign direct investment (FDI) has a mean of 3.86 % of GDP but exhibits substantial variability, with some countries receiving significantly higher FDI inflows than others. This variability in FDI could influence the capacity of recipient countries to complement Chinese energy loans with additional resources for infrastructure development. Economic development, measured by GDP per capita, shows considerable disparity, with a mean of $3629 and a high standard deviation of $3752. The interquartile range (from $1002 to $5154) highlights the economic heterogeneity of the sample, suggesting that wealthier nations may have a greater capacity to utilise energy loans effectively compared to lower-income countries.

The descriptive statistics in Table 2 reveal significant heterogeneity among the sampled countries in terms of energy financing, electrification, and socio-economic characteristics. These variations underscore the importance of contextual factors, such as governance, economic capacity, and rural demographics, in shaping the outcomes of Chinese energy loans. They also provide a foundation for understanding how these loans contribute to rural electrification and align with broader development goals, including SDG 7.

4.2. Correlation matrix

The results of the Pearson pairwise correlation and the Variance Inflation Factor (VIF) analysis presented in Table 3, indicate that there is no significant multicollinearity issues among the variables used in this study. Multicollinearity occurs when independent variables are highly correlated, potentially inflating standard errors and undermining the

Table 3
Correlation matrix.

Variables	1	2	3	4	5	6	VIF
Rural electrification	1						
China energy loan	0.23	1					1.11
Economic development	0.54	0.22	1				3.30
Foreign direct investment	−0.03	−0.09	0.07	1			1.05
Rural population	−0.37	−0.27	−0.59	0.03	1		2.85
Food production index	0.18	0.09	0.37	0.02	−0.22	1	1.19
Domestic credit	0.49	0.09	0.36	0.05	−0.17	0.2	1.17

Table 2
Descriptive statistics.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Mean	sd	p25	p50	p75	min	max
Rural electrification %	61.59	36.87	21.90	79.30	98	1	100
Domestic credit	31.49	25.71	14.04	23.26	40.69	2.373	127.0
Food production index	92.47	17.32	84.12	95.45	102.1	40.57	168.7
Foreign direct investment	3.864	3.968	1.079	2.924	5.459	−5.380	22.52
Economic development	3629	3752	1002	1934	5154	224.3	18,787
Rural population	54.05	21.12	37.27	58.62	71.50	8.251	86.90
China energy loan (US $M)	881.2	2187	99.45	289.1	847.9	3.110	25,000
China energy loan % of GDP	5.631	1.533	4.600	5.667	6.743	1.135	10.13

reliability of regression coefficients. A common threshold for identifying problematic correlations is a Pearson coefficient above 0.8 or a VIF exceeding 10 (Hair et al., 2014). Neither criterion is met in this analysis.

The correlation matrix shows that the highest pairwise correlation coefficient is −0.59 between economic development and rural electrification, followed by 0.54 between China energy loans and economic development. Both are well below the standard threshold of 0.8, suggesting that none of the variables exhibit strong linear dependence. The VIF values further confirm the absence of multicollinearity issues. The highest VIF is 3.30 for economic development, which is well below the threshold of 10. These findings provide confidence in the robustness of the regression models, ensuring that the estimated coefficients for Chinese energy loans and other explanatory variables are reliable. By minimising the potential distortion caused by multicollinearity, the analysis effectively isolates the contribution of each variable to rural electrification, allowing for a clearer interpretation of the results.

4.3. Baseline results

Table 4 presents the results of the baseline and extended regressions examining the relationship between Chinese energy loans and rural electrification. The main independent variable (*China energy loans*) is measured as a percentage of GDP. The analysis employs both fixed-effects (Columns 1, 2, and 5) and dynamic System Generalized Method of Moments (SGMM) estimators (Columns 3 and 6) to address potential endogeneity and dynamic persistence. To ensure robustness, a stagewise estimation approach is employed. In Stage 1 (Column 1), the model is estimated without control variables, providing an initial assessment of the relationship. In Stage 2 (Column 2), control variables are included in the pooled regression to account for additional factors influencing rural electrification. We also run a full pooled regression, and the results are presented in column 4. The SGMM framework is particularly appropriate for this study, given the potential simultaneity between loan inflows and electricity access expansion, as well as the temporal dependence of rural electrification outcomes.

Across all models, the coefficient for Chinese energy loans remains positive and statistically significant, reaffirming their vital role in promoting rural electrification. In the preferred S-GMM specification (Column 3), the short-run coefficient of 0.017 ($p < 0.05$) implies that a 1 % increase in Chinese energy loans leads to a 0.017 % short-run increase in rural electrification. Considering the significant lagged dependent variable ($\beta = 0.827$, $p < 0.01$), the long-run cumulative effect can be calculated as $0.017/(1 - 0.827) \approx 0.098$, suggesting that in the long term, rural electrification increases by nearly 0.10 % following a sustained 1 % rise in energy loans. This highlights that Chinese loans have a compounding impact—initial financing triggers short-run infrastructure gains that persist and amplify over time, consistent with development finance theory, which views external capital as a catalyst for bridging infrastructure gaps (Rostow, 1960; [45,46]). The Hansen ($p = 0.654$) and AR(2) ($p = 0.312$) tests confirm instrument validity and model robustness, reinforcing the reliability of these dynamic estimates.

Among the control variables, economic development (GDP per capita) remains a strong and consistent determinant of rural electrification across all models, reflecting the link between national income growth and energy access expansion. Domestic credit also exerts a positive and significant effect ($\beta = 0.310$, $p < 0.05$), suggesting that deeper financial systems enhance infrastructure investment and household connectivity. Meanwhile, variables such as FDI, food production, and rural population show weak or inconsistent effects, indicating that their influence on electrification may operate indirectly through broader structural channels.

Table 4
Baseline regression.

	Baseline results				Effect of corruption	
	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Fixed effect	Fixed effect	SGMM	Pooled	Fixed effect	SGMM
China energy loan	0.004**	0.004**	0.017**	0.004**	0.005**	0.097**
	(2.362)	(2.327)	(2.006)	(2.207)	(2.264)	(2.046)
Lag of dependent variable			0.827***			0.821***
			(7.654)			(3.356)
China energy loans*Corruption					−0.012**	−0.091*
					(-1.994)	(-1.921)
Corruption					11.101	14.163
					(0.471)	(0.849)
Economic development		25.415***	0.919	25.415***	25.962***	12.254*
		(4.786)	(0.465)	(5.630)	(3.957)	(1.747)
Foreign direct investment		−0.158	−0.454	−0.158	−0.140	−1.125
		(-0.621)	(-0.754)	(-0.345)	(-0.416)	(-1.300)
Rural population		−0.101	0.109	−0.101	−0.018	0.589**
		(-0.131)	(1.138)	(-0.150)	(-0.018)	(1.991)
Food production index		0.268	−0.335	0.268	0.272	−0.197
		(1.427)	(-1.244)	(1.621)	(1.117)	(-0.366)
Domestic credit		0.310**	0.089	0.310***	0.300*	−0.015
		(2.370)	(1.358)	(2.853)	(1.744)	(-0.140)
Constant	39.710***	−160.234***	30.821	−193.043***	−206.837**	−105.519
	(38.145)	(-2.894)	(1.018)	(-3.115)	(-2.165)	(-0.933)
Country effect	Yes	Yes			Yes	
Year effect	Yes	Yes			Yes	
AR(1)			0.036			0.051
AR(2)			0.312			0.257
Hansen test			0.654			0.768
Number of instruments			12			12
Observations	227	182	164	182	182	164
R-squared	0.465	0.685				
Number of countries	68	63	59	63	63	59
R-squared	0.154	0.33		0.962	0.689	

Robust t-statistics in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

4.4. Impact of corruption

Columns 5 and 6 of Table 4 present the results examining how corruption moderates the relationship between Chinese energy loans and rural electrification. The analysis employs the *control of corruption* index from the World Governance Indicators (WGI) as a proxy for governance quality. We classify the sample into high and low countries based on the sample median (of the reverse form of corruption); high-corrupt countries take 1 and 0 for low-corrupt countries. A binary variable is created to classify countries as high- or low-corruption, based on the sample median, and an interaction term (*China energy loans* × *Corruption*) is introduced to capture the moderating effect.

The results reveal that the coefficient on Chinese energy loans remains positive and statistically significant ($\beta = 0.097$, $p < 0.10$ in the SGMM specification), reaffirming the developmental importance of Chinese financing for expanding rural electricity access. However, the interaction term between Chinese energy loans and corruption is negative and statistically significant ($\beta = -0.091$, $p < 0.10$), indicating that corruption substantially diminishes the positive impact of these loans on rural electrification.

This result implies that, although Chinese loans contribute to improved rural electrification overall, their effectiveness is contingent upon the governance environment. In highly corrupt settings, project resources may be diverted, costs inflated, or implementation compromised, thereby weakening the transformative potential of external financing [30]; [34]. The diagnostic tests confirm the robustness of these findings—the AR(2) test (p = 0.257) shows no second-order serial correlation, and the Hansen test (p = 0.768) validates the instrument set used in the SGMM estimation.

These results underscore that while Chinese energy loans can accelerate rural electrification, their developmental impact is conditional upon institutional quality. Strengthening governance, improving transparency, and enforcing anti-corruption mechanisms are therefore critical to ensuring that such financing translates into sustainable energy access and aligns with the objectives of SDG 7 on affordable and clean energy.

4.5. Robustness – alternative measurement of variables

The robustness checks presented in Table 5 demonstrate the reliability of the positive association between Chinese energy loans and rural electrification, even when alternative measurements for the variables are employed. These findings reinforce the validity of the baseline results, underscoring the significant role of Chinese energy financing in improving energy access in rural areas.

Columns 1–2 of Table 5 employ the natural logarithm of China's energy loan as an alternative measurement of the independent variable. The coefficients remain positive and significant, confirming that the observed positive relationship between Chinese energy loans and rural electrification is robust to changes in how the independent variable is measured. This consistency underscores the reliability of the results, further validating the transformative impact of Chinese energy loans on rural energy access.

In Columns 2–3 of Table 5, access to clean energy and technologies in rural areas is used as an alternative measurement for rural electrification. The coefficients of Chinese energy loans remain positive and significant. This result highlights the broader impact of Chinese energy financing, not only in extending electricity access but also in enabling the adoption of cleaner and more efficient energy technologies in rural populations. These findings align with the development economics theory, which posits that targeted infrastructure investments promote technological advancement and socio-economic transformation (Rostow, 1960). For instance, Chinese-funded renewable energy projects, such as the Garissa Solar Plant in Kenya, have significantly increased access to modern, clean energy solutions, reducing reliance on traditional biomass fuels and improving rural livelihoods.

Table 5
– Robustness -alternative measurement of variables.

	Alternative measurement of China loans		Alternative measurement of Rural electrification	
	(1)	(2)	(3)	(4)
VARIABLES	Fixed effect	SGMM	Fixed effect	SGMM
China energy loan (Log)	0.499**	1.584*		
	(1.988)	(1.947)		
China energy loan (% GDP)			0.003**	0.003**
			(2.531)	(2.466)
Lag of dependent variable		0.936***		0.996***
		(14.646)		(26.583)
Economic development	25.147***	0.444	6.480	−0.773
	(4.938)	(0.215)	(1.429)	(-1.517)
Foreign direct investment	−0.138	0.068	−0.132	0.115
	(-0.553)	(0.138)	(-0.628)	(0.942)
Rural population	−0.280	0.094	−0.720	−0.003
	(-0.353)	(0.909)	(-0.774)	(-0.075)
Food production index	0.272	−0.100	0.054	0.056
	(1.454)	(-0.410)	(0.790)	(0.878)
Domestic credit	0.298**	−0.000	0.041	0.045***
	(2.209)	(-0.017)	(0.535)	(3.845)
Constant	−150.422***	−1.625	17.013	0.090
	(-2.742)	(-0.062)	(0.424)	(0.015)
Country effect	Yes		Yes	
Year effect	Yes		Yes	
AR(1)		0.032		0.082
AR(2)		0.647		0.751
Hansen test		0.721		0.261
Number of instruments		12		12
Observations	182	164	185	164
R-squared	0.681		0.663	
Number of countries	63	59	65	59

Robust z-statistics in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

5. Discussion and interpretation of the results

5.1. Chinese energy loans and rural electrification

The baseline results presented in Table 4 confirm a significant and positive association between Chinese energy loans and rural electrification, highlighting their critical role in addressing energy poverty in emerging economies. This relationship is firmly grounded in development economics theory, which emphasises that targeted investments in infrastructure serve as catalysts for economic growth and societal transformation [8]. Gallagher et al. (2018) provide one of the earliest systematic analyses of Chinese energy development finance, noting that loans catalyse infrastructure development across the emerging countries but also raise risks related to debt and environmental sustainability. Our findings corroborate the positive dimension of this narrative by showing that Chinese loans are indeed associated with measurable gains in rural electrification. However, by focusing specifically on rural outcomes, we extend Gallagher et al. (2018)'s macro-level insights into a subnational domain where energy poverty is most entrenched.

Similarly, Chen et al. [18] highlight the role of Chinese loans in expanding generation capacity, but their analysis is limited to aggregate national-level data and focuses primarily on generation projects. Our results build on this by incorporating not only generation but also the distributive effects of such loans on rural populations. In doing so, we provide empirical evidence that Chinese financing extends beyond urban and industrial hubs, even though prior studies (e.g., Ref. [19]) have noted that rural beneficiaries are often secondary in national energy planning. However, Byaro and Mmbaga [20] caution that energy finance in Africa has tended to widen rural-urban disparities, with urban centres absorbing the bulk of infrastructural improvements. In contrast, our findings indicate that Chinese loans, when sufficiently scaled, have

discernible impacts in rural contexts. This suggests that Chinese financing may deviate from some of the urban bias observed in other forms of foreign investment. Yet, these findings must be balanced against Dreher et al. [6], who argue that allocation decisions often follow political alignment, raising questions about whether rural electrification gains are evenly distributed across recipient countries.

One of the primary tenets of development economics theory is that infrastructure development, particularly in underdeveloped rural areas, is essential for reducing economic and social disparities. Rural regions in many emerging economies suffer from chronic underinvestment in basic services, including energy infrastructure, which perpetuates cycles of poverty and limits opportunities for growth. Chinese energy loans address these capital deficits by providing the financial resources needed for large-scale energy projects. For instance, the Kafue Gorge Lower Hydropower Project in Zambia, financed by Chinese loans, has significantly improved electricity supply to rural areas, enhancing agricultural productivity and promoting rural enterprises [21].

The positive association between Chinese energy loans and rural electrification reflects the transformative potential of infrastructure investments as posited by development economics theory. By financing large-scale energy projects, these loans not only address critical energy deficits but also promote broader socio-economic development in rural areas. Furthermore, these investments play a pivotal role in advancing SDG 7 by ensuring access to affordable, reliable, and sustainable energy in underserved rural communities, laying the foundation for inclusive and sustainable development.

An important dimension of heterogeneity arises from the distribution of Chinese loans, which are disproportionately concentrated in resource-rich countries such as Angola and Brazil (Boston University Global Development Policy Centre). These countries often receive larger volumes of financing, which can translate into greater improvements in rural electrification relative to smaller borrowers. This raises policy concerns about whether Chinese loans favour contexts with stronger resource collateral rather than poorer, less resource-endowed countries where energy poverty is most acute. As shown in Appendix B (sample countries), the top 4 recipients —Angola, Brazil, Russia, and Venezuela —account for about 50 % of the total amount to all countries. Therefore, we conduct additional analysis excluding the largest loan recipients (countries that have received more than $10,000 million) and the results remain broadly consistent, suggesting that our findings are not driven solely by these outliers. Nonetheless, the unequal distribution of financing underscores the need for differentiated policy approaches: while resource-rich countries may leverage Chinese loans for rapid expansion, poorer countries may require concessional terms, targeted rural electrification provisions, or complementary support from multilateral institutions to ensure inclusive and equitable progress toward SDG 7.

5.2. Interaction between Chinese energy loans and corruption

Regarding corruption, our analysis of the interaction between corruption and Chinese energy loans reveals a complex but discernible pattern in how governance quality mediates electrification outcomes. While the standalone effect of Chinese loans remains positive and significant, the interaction term with corruption has a statistically significant dampening effect, suggesting that governance deficiencies erode some of the potential benefits. This finding refines earlier perspectives on China's infrastructure-driven approach, demonstrating that while its loans can bypass bureaucratic hurdles in corrupt settings, the resulting projects may achieve marginally less electrification impact per dollar invested compared to more transparent environments [13,42]. This finding builds on Isaksson and Kotsadam [42], who demonstrate that Chinese aid inflows are associated with increased corruption at the local level in Africa. Our results nuance this conclusion by showing not only that corruption rises with aid inflows but also that corruption directly constrains the effectiveness of energy loans in achieving electrification outcomes. Tawiah et al. [13] similarly highlight that corruption reduces the efficiency of Chinese investment and trade in Africa, a conclusion strongly echoed in our findings for rural energy access.

Our results align with recent case evidence from Angola and Nigeria, where corruption-related cost inflation and quality compromises have reduced project efficiency, despite overall access improvements. While our study does not find evidence of outright developmental failure, the corruption interaction underscores the need for recipient countries to strengthen their transparency and accountability mechanisms if they are to fully reap the benefits of Chinese financing.

5.3. The role of control variables

Beyond the primary focus on Chinese energy loans and corruption, several control variables yielded meaningful insights into the determinants of rural electrification. The lagged dependent variable is positive and highly significant in both SGMM specifications, confirming the persistence of rural electrification outcomes over time. This indicates that once electrification infrastructure is established, it generates cumulative benefits and path dependence, as access to electricity tends to expand progressively across neighbouring communities [50].

Economic development (GDP per capita) consistently shows a positive, statistically significant effect across models, reaffirming that wealthier economies are better positioned to finance and maintain rural electrification systems. However, as Sen [40] and by Byaro and Mmbaga [20] observe, income growth alone does not guarantee inclusive energy access—complementary institutional and infrastructural investments remain essential for ensuring equitable distribution of electricity benefits. Domestic credit also shows a positive and significant association with rural electrification, suggesting that financial sector development facilitates the mobilisation of domestic resources necessary for expanding energy access. This finding aligns with Byaro and Mmbaga [20], who argue that access to credit enhances investment capacity for energy infrastructure and supports rural electrification initiatives.

In contrast, foreign direct investment (FDI) demonstrates a negative but statistically insignificant effect, echoing prior research [19,41] that finds FDI disproportionately benefits urban, capital-intensive sectors. This underscores that not all external capital flows translate into improved rural infrastructure outcomes. Finally, rural population exerts a positive and significant effect in the extended models, indicating that larger rural populations can stimulate electricity demand, thereby justifying infrastructure expansion. However, in contexts where grid capacity remains weak, population pressures may also reveal structural bottlenecks in energy distribution [20]. Collectively, these results highlight the complex interplay between financial, demographic, and macroeconomic factors in shaping rural electrification outcomes across emerging economies.

However, the results should be interpreted with caution, because this study relies on aggregate national-level data, which masks variation in the effects of different energy project types. Large-scale hydropower projects often feed into national grids, while off-grid solar initiatives can have more immediate benefits for rural households. Combining these under a single loan measure may obscure important differences in their impact on rural electrification. While robustness checks using alternative specifications and estimation strategies were employed to mitigate such risks, these limitations remain inherent to the dataset.

6. Conclusion

This study has examined the impact of Chinese energy loans on rural electrification across 68 emerging countries from 2001 to 2023. Using country-fixed-effect and System-GMM estimation, we find that Chinese energy loans are positively associated with rural electricity access, but this relationship is significantly moderated by corruption. These findings highlight the transformative role of Chinese energy financing in

expanding electricity access in rural areas, which often suffer from chronic underinvestment and infrastructural deficits [3]. By providing capital for large-scale energy projects, Chinese loans address critical barriers to rural electrification, facilitating the construction of energy infrastructure, grid expansions, and off-grid renewable solutions. Projects like the Kafue Gorge Lower Hydropower Project in Zambia [21] and the Karuma Hydropower Project in Uganda [23] exemplify the tangible impacts of Chinese financing in improving rural energy access and supporting socio-economic development.

Despite the robust findings and positive implications, the characterisation of Chinese financing as purely pragmatic and infrastructure-driven has been challenged in a growing body of critical literature. Scholars argue that Chinese development loans, particularly in Sub-Saharan Africa, often come with opaque terms, collateralization through resource concessions, and heightened sovereign debt risks — a phenomenon referred to as 'debt-trap diplomacy' [6,7,25]. While these loans have enabled critical infrastructure projects, they have also raised concerns regarding long-term debt sustainability, resource dependency, and reduced fiscal autonomy in recipient countries. The absence of governance conditions may facilitate quicker disbursement, but it can also increase exposure to predatory lending and undermine institutional development (Hassoun, 2012; [42]). Thus, while the immediate infrastructure benefits of Chinese loans are notable, their broader macroeconomic and political implications warrant careful consideration.

Therefore, this study points to several targeted policy implications for recipient governments, Chinese lenders, and the international community. For recipient countries, generic governance reforms are insufficient; instead, reforms must directly safeguard the effectiveness of loan-financed projects. Establishing independent monitoring units within energy ministries, mandating project-level audits linked to loan disbursements, and introducing community-based reporting mechanisms are critical measures to reduce corruption. Such steps ensure that resources reach rural beneficiaries and are effectively used to expand infrastructure for supplying modern energy services, a key component of SDG 7, Target 7.b. Policymakers should also negotiate loan agreements that explicitly earmark a minimum share of funding for rural electrification. This directly addresses the observed urban bias in infrastructure rollout and prioritises SDG 7, Target 7.1 (to ensure universal access to affordable, reliable, and modern energy services).

For Chinese lenders, greater transparency in loan terms—such as publishing project contracts and repayment structures—can improve accountability while reducing reputational risks. This fosters a more stable and cooperative investment climate, aligning with SDG 7, Target 7.a (to enhance international cooperation for investment in energy infrastructure). Furthermore, incorporating performance-based disbursement clauses tied to rural access milestones would directly incentivise the delivery of tangible outcomes for Target 7.1 without imposing politically sensitive external governance conditions.

Finally, prioritising renewable energy projects is most effective when aligned with rural contexts. Off-grid solar and mini-hydropower solutions, for example, can directly support rural communities while reducing reliance on biomass. This strategy explicitly advances SDG 7, Target 7.2, which aims to increase substantially the share of renewable energy in the global energy mix. By embedding these specific, target-oriented measures, Chinese energy loans can be more effectively harnessed to advance the multifaceted goals of SDG 7.

Research involving human participants and/or animals

Provide details regarding the ethical treatment and approval for research involving human or animal subjects.

No humans or animals were used in this research.

Informed consent

Confirm that informed consent was obtained from all participants involved in the research, where required.

Informed consent is not applicable because no human were used. Only secondary data was used.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to proofread. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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CRediT authorship contribution statement

Haoru Yang: Project administration, Writing – review & editing. **Vincent Tawiah:** Formal analysis, Methodology, Supervision, Writing – original draft. **Hela Borgi:** Conceptualization, Funding acquisition, Writing – original draft.

Declaration of competing interest

There is no conflict of interest on the paper titled.

Appendix A

Table A1
Summary of Literature

Author(s) & Year	Context	Methodology	Main Findings	Limitations/Gaps
Gallagher et al. (2018)	China's development finance in global energy sector	Cross-country empirical analysis	Chinese loans catalyse large-scale projects, with developmental benefits/ risks	Does not focus specifically on rural electrification
Chen et al. [18]	Chinese overseas energy financing (generation)	Comparative analysis of power projects	Financing expanded generation capacity but often favours fossil fuels	Limited to generation; excludes transmission/ distribution
Cheng & Qi (2021)	Chinese outward FDI and energy sector upgrading	Panel data econometric analysis	Chinese FDI contributes to energy sector upgrading and growth	Focus on macro-level; limited rural electrification analysis

(*continued on next page*)

Table A1 (*continued*)

Author(s) & Year	Context	Methodology	Main Findings	Limitations/Gaps
Dreher et al. [6]	Chinese aid and loans to Africa	Cross-country econometric study	Loan allocation influenced by political alignment; mixed outcomes	Neglects subnational electrification outcomes
Isaksson & Kotsadam [42]	Chinese aid and local corruption in Africa	Micro-level corruption analysis	Chinese aid increases local corruption	Focus on corruption but not electrification outcomes
Aluko et al. [19]	Foreign direct investment, governance & electricity in Africa	Panel regression analysis	FDI improve electricity access but, national level	Focus on generic FDI, not energy-specific. Is limited to national aggregates
Wen, Alessa & Tawiah [5]	Energy independency in Africa	Panel econometrics	Chinese investments enhance energy independence, especially via renewables.	Focus on national energy independence, not rural access or governance.
Zhou, Alessa & Tawiah [28]	Chinese investment and clean energy Africa	Panel econometrics	Chinese investment positively associated with access to clean energy.	National-level study; does not distinguish rural vs. urban access.
Byaro & Mmbaga [20]	General determinants of electricity access in in Africa	Panel regression analysis	Domestic credit and food production increase electricity access	Does not account for external funding and governance effects. No specific reference to rural electricification
Oyewunmi [35]	Rural electrification in Nigeria	Case study analysis	Weak governance undermines electrification outcomes	Case-specific; lacks generalisability
Boamah, Williams & Afful [30]	Corruption and energy in Ghana	Qualitative institutional analysis	Corruption undermines energy sector governance, creating "justifiable" energy injustices.	Country case study; lacks generalisable cross-country evidence.
Hao, Gai & Wu [34]	Corruption and energy allocation in China	Econometric analysis	Corruption and misallocation reduce energy efficiency.	Focuses on domestic Chinese context, not external loans.
Yung, Cai & Li [36]	Corruption and investment	Panel data econometrics	Corruption can expedite investments by reducing bureaucratic delays.	Highlights paradoxical role of corruption; does not focus on energy access.
Sovacool et al. [31]	Renewable energy and corruption risks	Qualitative/ interview-based evidence	Corruption undermines renewable energy investments	Focus on renewables broadly, not rural electrification
Tawiah et al. [13]	Corruption, Chinese investment, and trade in Africa	Cross-country econometric study	Corruption reduces efficiency of Chinese investment and trade benefits	Focus on corruption broadly, not energy-specific electrification outcomes
Moura [29]	Determinants of Chinese outward investment in developing countries	Political economy analysis	Chinese financing driven by geopolitical and strategic interests.	Limited focus on electrification outcomes or rural targeting.
Choi [24]; Singh [7]; AfDB (2023); Dau et al. [26]	Various developing countries	Critical policy analysis	External loans risk dependency, fiscal vulnerability, and resource overexploitation.	Theoretical critique; limited empirical testing in rural electrification.

Appendix B

Table B1
List of sample countries and loan amount

Country	No.Loans	Amount($M)	Country	No.Loans	Amount($M)	Country	No.Loans	Amount($M)
Angola	12	24210.7	Fiji	1	70	Nepal	1	115
Antigua and Barb	1	43.7	Gabon	3	504.69	Niger	2	175.3
Argentina	3	3030.11	Ghana	2	1599.56	Nigeria	1	984.32
Bangladesh	6	5817.3	Guinea	2	1510	Pakistan	6	9744.23
Belarus	6	1935.29	Guyana	1	39	Papua New Guinea	1	133.38
Bolivia	2	1059.73	Indonesia	5	3168.54	Russia	6	34613.22
Bosnia and Herze	1	234.56	Iran	4	5883.38	Rwanda	1	214
Brazil	6	27781				Senegal	3	262.7
Burkina Faso	1	50.13	Iraq	1	872.13	Serbia	3	1088.4
Cambodia	9	1160.33	Kazakhstan	5	5020.91	South Africa	3	4500
Cameroon	3	727.88	Kenya	9	1639.65	Sri Lanka	7	2496.13
Chad	1	130	Kyrgyz	3	983.8	Sudan	6	2060
Congo, Dem	4	1178.43	Lao PDR	11	6276.85	Syrian Arab	1	51.24
Congo	2	628.98	Lesotho	1	66.83	Tajikistan	7	881.2
Mauritius	1	5.85	Madagascar	1	240	Tanzania	1	1195
Cote d'Ivoire	2	1058.48	Malaysia	2	2004.88	Togo	2	112.86
Cuba	2	219.7	Maldives	1	75.4	Turkmenistan	2	8189.53
Djibouti	1	20.4	Mali	1	145	Uganda	5	2427.57
Ecuador	4	3974.33	Mauritania	1	138.3	Uzbekistan	9	4918.49
Egypt	1	690	Mexico	1	1000	Venezuela	5	14000
Equatorial Guinea	5	1812.12	Mongolia	4	298.42	Viet Nam	9	4923.58
Eritrea	1	98	Morocco	1	304.5	Zambia	4	2188.31
Ethiopia	9	2057.05	Myanmar	7	2478.45	Zimbabwe	2	1317.2

Appendix 3

Table C1
Excluding top recipients of loans

	(1)	(2)
VARIABLES	Fixed effect	SGMM
China energy loan	0.002**	0.019**
	(2.381)	(2.087)
Lag of dependent variable		0.865***
		(4.879)
Economic development	3.144***	0.003
	(7.132)	(0.002)
Foreign direct investment	−0.368	−0.054
	(-1.329)	(-0.081)
Rural population	0.209	0.044
	(0.875)	(0.358)
Food production index	0.229	−0.223
	(1.275)	(-0.802)
Domestic credit	0.339***	0.066
	(3.094)	(0.438)
Constant	−159.966***	22.217
	(-4.639)	(0.796)
Country effect	Yes	
Year effect	Yes	
AR(1)		0.026
AR(2)		0.247
Hansen test		0.785
Number of instruments		12
R-Square	0.310	
Observations	158	140
Number of countries	59	55

Robust z-statistics in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

Data availability

Data will be made available on request.

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