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How will power outages affect the national economic growth: Evidence from 152 countries

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ABSTRACT

Electricity system security is facing severe challenges due to climate change, natural disasters, and network cyber-attacks. Although the microeconomic impacts of power outages on economic output have been well studied, there is insufficient understanding on their macro-economic effects, thus failing to efficiently support the electricity reliability policies. With this motivation, this study first constructs a theoretical model to analyze the mechanism between power outages and economic growth based on the classical production function. Then, an empirical econometric model is developed from the theoretical analysis and applied to 152 countries. To address the potential endogeneity problems, an index of annual country lightning density is calculated using remote sensing data and is served as an instrumental variable of power outages. Our major findings are that: (1) every 1% decrease in System Average Interruption Duration Index (SAIDI) will lead to an increase in global economic growth of 2.16%. (2) the impacts of power outages are heterogenous among different countries, and larger impacts occur in countries of lower-income, larger land area and lower electrification rates. (3) the improvement of power infrastructure quality in low-income countries can significantly narrow the world wealth gap, and the Gini index will decline by 9.55 ‰ if the SAIDI in low-income countries is reduced to 10% quantile of that in high-income countries. Our results provide evidence for investment in power system operating and power supply quality improving.

1. Introduction

As a key pillar of national modernization and competitiveness (Thacker et al., 2019), high-quality power infrastructure has become a significant concern for economic growth.[1] However, electricity system security is facing severe challenges due to a combination of various external and internal risk factors. Climate change, natural disasters, and network cyber-attacks are perceived as major external risk factors threatening the safe operation of power system, and these factors have shown rising forces because of the accelerated global environment change and geopolitical risks (Ni et al., 2021; Rafal et al., 2022; Yongping et al., 2023). Meanwhile, the global electricity system is now experiencing low-carbon transition to achieve the sustainable target. The internal change, featured by rising penetration of intermittent and stochastic renewable energy, will increase the security risk of power supply (Ma et al., 2013). Compared with fossil fuel generators, wind and solar generators have smaller unit size and are exposed to natural environment directly, thus they are more vulnerable to external shocks (Bennett et al., 2021). Wiser electricity system planning, sufficient electricity infrastructure deployment and reasonable reliability policies are called to cope with these challenges. All these policies boil down to a good understanding of the socioeconomic impacts brought by power outages and the cost benefit analysis of different security measures.

Power supply quality varies in different countries due to diverse electricity infrastructure, mixed weather conditions, and management levels (Chen et al., 2022; Hallegatte et al., 2019). Fig. 1 presents the System Average Interruption Duration Index (SAIDI) around the world in 2020, which indicates the power supply quality in Europe, North America and Oceania is much better than that in Asia, Africa, and South America. This distribution is in correlation to the economic development

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of each country. Relevant studies have found that reliable power infrastructure lays fundamental for companies to enter markets, discover potential customers, and bring in investment and technology, thereby increasing total factor productivity (Bastos and Nasir, 2004; Escribano et al., 2010). On the contrary, the deficient power supply will result in production disruptions, damage to sensitive equipment, and loss of perishable goods. (Alby et al., 2010; Gilmore et al., 2010; McDonald et al., 2011; Oshikoya and Hussain, 2002; Pronk et al., 2009). Unreliable electricity system also forces companies to use backup diesel generators, which cause far more expensive fees and pollutant emissions (Farquharson et al., 2018). Although these studies have already analyzed the impact of power supply quality on the enterprises' economic output from the micro-mechanisms such as enterprise productivity, production cost, sales revenue, and labor employment (Abeberese et al., 2021; Dethier et al., 2011; Fay and Morrison, 2006), the main dependent variable is the total electricity consumption. Moreover, the macroeconomic effect of power supply quality is often ignored (Hallegatte et al., 2019).

There are several obstacles on the way to assess the impact of power supply quality on economic growth. Firstly, it is difficult to make distinction between quantity and quality, and then take measurement for power infrastructure quality on a global scale. Secondly, it is challengeable to introduce electricity quality variables into the traditional macro-economic model. To construct a representatively analytical framework for estimating the impact, we should clarify the probable mechanisms for power supply quality to affect macroeconomic growth. Finally, the quality variable is probably to be endogenous in the empirical estimation. It is correlated with several economic growth determinants, which is subjected to reverse causal influence and measurement error. An appropriate identification strategy is thus needed to improve the accuracy of the estimated results.

In response to the above challenges, we have conducted an empirical study on the impact of power supply quality on national economic growth. Based on the classical production function, a theoretical model is first established to analyze the mechanism between power outages and economic growth. Then, an empirical econometric model is developed from the theoretical analysis and applied to 152 countries, aiming at answering the following three questions:

(1) How will improving the power infrastructure quality affect the economic growth?
(2) How does the impacts of improving power supply quality on economic growth varies in different countries?
(3) How can providing more reliable electricity promote economic growth and equity around the world?

The remainder of this paper is organized as follows: Section 2 presents the literature review and shows the impact of power supply quality on economic growth from previous studies. Section 3 describes the methodology and data, and discusses the theory why power infrastructure quality affects economic growth. Section 4 shows the result analysis and discussion. Section 5 summarizes the conclusions and proposes some policy implications.

2. Literature review

The influence of power supply quality on the economy has received great attention. The existing studies have used various economic models to quantitatively explore the influence of power infrastructure unreliability on different economic indicators, such as enterprise production, household economy, and macro-economic growth. Enterprises, households, and countries are the three major research objects in the past literature. Thus, the previous literature is divided into three categories and are reviewed individually as below.

The first category used enterprise-level samples, and adopted the econometric method to discuss the influence of power supply quality on enterprise economic output from multiple paths. The first path is to reduce total factor productivity. Mensah (2016) used a firm survey data from 15 sub-Saharan African countries to analyze the impact of power supply disruption on firm productivity based on a quasi-experimental approach. He found that every 1% increase in SAIDI can lead to a decrease of enterprise productivity by 0.6%–1.1%. In Bangladesh, a power outage event will bring down the enterprise productivity by about 4.1% (Zhang et al., 2020). The second path is to increase the cost of production. Using data from 26 countries in Europe and Central Asia collected by Business Environment, Iimi (2011) estimated that eliminating all power outages would reduce the company's production costs by an average of 1.4%. The third path is to increase sales loss. Based on the World Bank Enterprise Survey, Bbaale (2018) evaluated the sales loss caused by power outages to small and medium-sized and non-export-oriented manufacturing enterprises in African countries and found that electricity problems would reduce sales by 11% -12% in that region. The fourth path is to hinder employment. In South

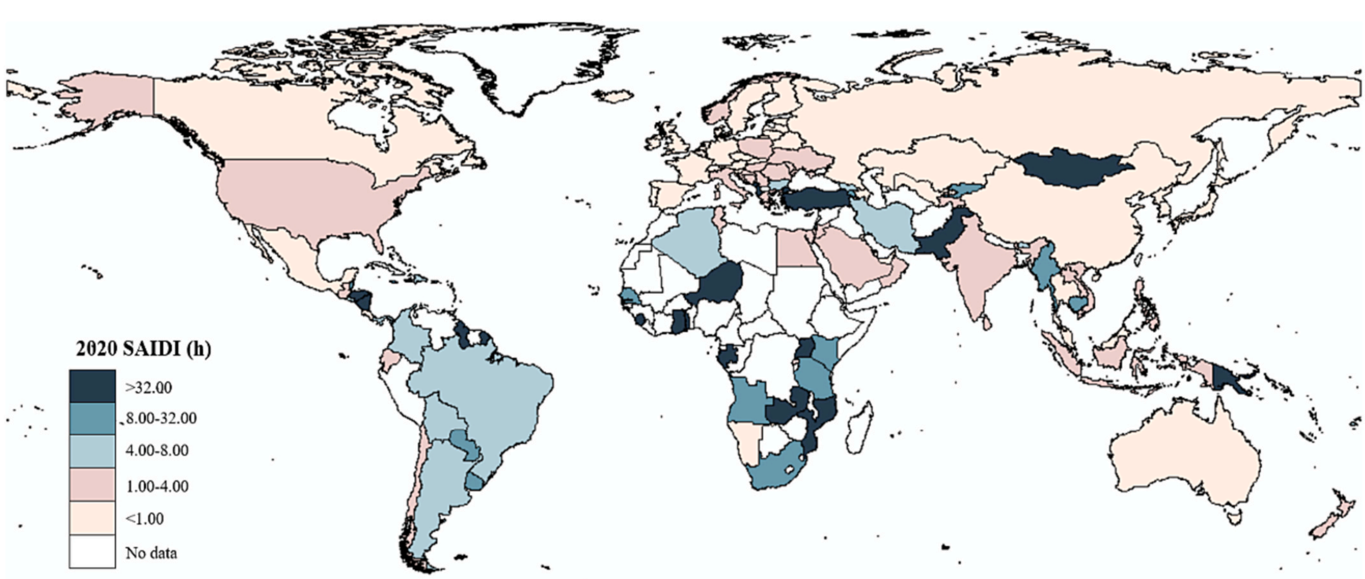

Fig. 1. Global SAIDI in 2020.

Asia, Zhang et al. (2020) found that long-term blackouts are related to the decline in per capita income and female labor force participation rate, because blackouts force women labor to spend more time on housework. This conclusion is also consistent with the World Bank's 2019 report that power outages threaten workers' employment (Blimpo and Davies, 2019).

The second category analyzed the impact of power outages on household economic activities. The increase in household electricity costs caused by power outages will affect the household budget and make low-income households fall into the poverty trap (Sovacool, 2012). Due to the limitation of public data, many studies have used natural policy experiments to evaluate the impact of power outages on household economic activity. For example, Lenz et al. (2017) compared 974 households before and after electrification based on the Power Access Pilot Program (EARP) in Rwanda, Africa, and found that frequent power outages would restrict households from engaging in productive, educational, and recreational activities. The other method is to estimate the willingness to pay for preventing power outages through questionnaire survey, so as to reflect the impact of power outages on the economy. Obolensky et al. (2019) used this method to study households in low and middle-income countries and found that the losses caused by power interruption accounted for 0.002% to 0.15% of annual GDP, which is equivalent to $2.3 billion to $190 billion.

The third category discussed the impact of power supply on national economic growth from the macro level. For the national economy, low power reliability hinders the development of high-growth industries, thereby depriving the country of economic potential (Blimpo and Davies, 2019). However, the quantitative estimation of power infrastructure improvement on national economic growth is very limited. The Asian Development Bank reported that in 102 developing countries, an additional point in the average growth rate of electricity generating capacity net of losses results in 0.22% additional average per capita growth (Straub and Hagiwara, 2010). Andersen and Dalgaard (2013) established a panel data model to estimate the total impact of blackouts on economic growth in 39 countries in sub-Saharan Africa between 1995 and 2007, and found that weak electricity infrastructure is a serious drag on economic growth. 2.86% economic growth will be achieved in the long run if the duration of power outages is reduced by 1%. There are also a few studies that simulate the impact of future power supply quality improvement on national economic development. For example, the World Bank Report found that the net return of investing $1 in low-income and middle-income countries for more flexible power infrastructure is $4 using input-output model analysis (Hallegatte et al., 2019).

Previous studies have provided evidence for understanding the impacts of power supply quality on economic growth. However, there are still several places to be improved. Firstly, most of the studies use micro-level data of enterprises or households to analyze the effect of power infrastructure quality on enterprise output, but rarely evaluate the impact on macroeconomic growth at the national level. Secondly, only a few studies have done their analysis on limited countries or regions, while studies at the global level are still lacked. Thirdly, most studies have not paid attention to the bi-directional causality between power supply quality and economic growth, which makes it difficult to control potential endogenous bias.

3. Methodology

3.1. Model

To analyze the impact of power supply quality on economic growth, this paper uses the form of classical production function as the growth accounting analysis framework:

$$Y = AF(K, L) \quad (1)$$

Where $Y$is aggregate real GDP; A is the time-varying total factor productivity (TFP); K and L represent capital and labor inputs, respectively. Then, logarithmic processing is taken, and we get its differential with respect to time yields:

$$\frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + \frac{F_K K}{F}\frac{\dot{K}}{K} + \frac{F_L L}{F}\frac{\dot{L}}{L} \quad (2)$$

Next, we introduce the power infrastructure quality level (*PIQ*) into the classical production function. According to the previous review (Straub and Hagiwara, 2010), power infrastructure will affect economic output from two channels. Firstly, it influences total factor productivity in the form of a Cobb-Douglas function:

$$A = A(PIQ) = A^{*} \times PIQ^{\eta} \quad (3)$$

Where A^{*} is the true TFP and η is the elasticity of A with respect to X, which is no observable.

Secondly, the power infrastructure will also enter the production function in the form of an additional factor. And combined, the production function form applied in this paper is shown as follows:

$$Y = A^{*} \times PIQ^{\eta} \times F(K^{*}, L, PIQ) \quad (4)$$

Where capital K is amended to K^{*} by excluding infrastructure investment.

Following formula (2), the logarithm is taken on both sides of formula (4) and a differential is obtained as eq. (5).

$$\frac{\dot{Y}}{Y} = \left(\eta + S^{PIQ}\right)\frac{P\dot{I}Q}{PIQ} + \frac{\dot{A}}{A} + S^{K^{*}}\frac{\dot{K}}{K} + S^{L}\frac{\dot{L}}{L} \quad (5)$$

Where S is the income share of each production factor. Since this paper focuses on the impact of power supply quality on economic growth, we separate the quality of power infrastructure from the remaining factors, and use a series of observable control variables affected by various production factors to measure the contribution of the remaining factors to economic growth.

$$\frac{\dot{Y}}{Y} = \beta\frac{PIQ^{\bullet}}{PIQ} + \lambda X + \varepsilon \quad (6)$$

Where $X = X\left(\tilde{K}, L\right)$is the control variable vector; ε is the error term.

Next, we examine the meaning of $\dot{Y}/Y$ and$PIQ^{\bullet}/PIQ$.

$$\frac{\dot{Y}}{Y} = \frac{dlnY}{dt} \quad (7)$$

$$\frac{PIQ^{\bullet}}{PIQ} = \frac{dlnPIQ}{dt} = \frac{lnPIQ_{T+1} - lnPIQ_{T}}{lnPIQ_{T}} \quad (8)$$

For the growth rate of output $\dot{Y}/Y$, we use the annual growth rate of real GDP as a measure. Inspired by Andersen and Dalgaard (2013), we use the current index to measure the power infrastructure quality in each period. By sorting out formulation (5)–(8), the linear Equation between the quality of power infrastructure and economic growth can be calculated as Eq. (9):

$$gGDP = \beta lnPIQ + \lambda X + constant + \varepsilon \quad (9)$$

We focus on the influence coefficient (β) of power infrastructure quality on economic growth. $\beta > 0$ indicates that the improvement of power infrastructure quality will promote economic growth.

Based on the above theoretical analysis, we construct an empirical model to analyze the impact of power infrastructure quality on economic growth, see Eq. (10):

$$gGDP_{i,t} = \beta_0 + \beta_1 lnPIQ_{i,t} + \lambda X_{i,t} + \nu_i + \tau_t + \varepsilon_{i,t} \quad (10)$$

Where i and t represent the national index and time index respectively. $gGDP$ is the degree of economic growth speed.PIQ denotes the level of power infrastructure quality. β_1 represents the influence coefficient of power supply quality on the economic growth rate, which is the core parameter concerned in this paper. Other control variables that affect the economic growth rate of a country or region is denoted by X . $\varepsilon_{i,t}$ is the error item. In addition, this paper also controls the country fixed effects ν_i , and year fixed effects τ_t .

The econometric estimation of eq. (10) faces potential endogenous problems between power supply quality and economic growth. Countries and regions with rapid economic development often have their advantages in capital and technology, and thus can build power infrastructure systems with higher quality (Hallegatte et al., 2019). Meanwhile, a reliable power infrastructure can boost economic output (Braese et al., 2019). Therefore, the correlation between the power supply quality and economic growth may cause the problem of two-way causality. At the same time, there are inevitable measurement errors of power infrastructure quality and missing variable errors caused by the difficulties in fully covering the factors affecting economic growth (Andersen and Dalgaard, 2013). Although the fixed effect model can eliminate the time-invariant effects to some extent, the endogeneity problem still cannot be solved and result in estimation bias.

The instrumental variable approach is a suitable solution strategy for endogenous problems (Bollen, 2012; Hill et al., 2021; Sande and Ghosh, 2018). In this paper, the lightning density is used as an instrumental variable of SAIDI for regression, which is calculated as the total number of lightning occurrences per square kilometer per year. Using lightning density meets two major requirements for instrumental variables in econometrics. From the perspective of correlation requirement, there is a positive relationship between lightning density and power outage duration. In South Africa, lightning damage accounts for about 65% of distribution network failures (McDonald et al., 2011). In areas with high lightning density, the frequency of power outages is higher (Chisholm and Cummins, 2006). As for the exclusive requirement, lightning, which is a natural feature of a region, is difficult to be adversely affected by the economic and social characteristics of the region, satisfies the exogeneity assumption of instrumental variables. At last, we adopted the two-stage method for estimation, as shown in Eqs. (11) and (12):

$$lnPIQ_{i,t} = \gamma_0 + \gamma_1 lnLD_{i,t} + \nu_i + \tau_t + \varepsilon_{i,t} \tag{11}$$

$$gGDP_{i,t} = \beta_0 + \beta_1 ln\widehat{PIQ} + \lambda X_{i,t} + \nu_i + \tau_t + \varepsilon_{i,t} \tag{12}$$

Where $lnLD_{i,t}$ represents the logarithm of the annual lightning density of each country.

3.2. Data

Based on data availability, this paper uses panel data of 152 countries from 2016 to 2020 for empirical research. The descriptive statistics of variables are shown in Table 1.

This paper selects the annual growth rate of real GDP published by the World Bank Open Data as the dependent variable in the empirical analysis. The quality level of power infrastructure is the core explanatory variable of this paper, and the *lnSAIDI* in each country and region published by Doing Business is chosen as the proxy variable. The *SAIDI* is the system average interruption duration (in hours) experienced by the customer in one year, which is calculated as the ratio of the total outage time to the number of users. A larger *SAIDI* value means more serious power outages experienced by the country within one year, which symbolizes the lower quality level of power infrastructure.

To solve the endogenous problem in evaluating the economic impact of power supply quality, we use lightning density as an instrumental variable. The original data on lightning density comes from the National Aeronautics and Space Administration (NASA). Based on R language, we select the 0.5° × 0.5° grid point lightning data set provided by the Lightning Imaging Sensor (LIS) on the International Space Station to judge which country the lightning is located. Fig. 2 shows the data of lightning occurrences around the world in January 2020. Next, we count the number of lightning occurrences in various countries around the world every year. The lightning density index of every country is calculated as the total lightning count divided by the country area.

This paper also controls a set of variables that affect a country's economic growth rate in the empirical model to minimize the bias of missing variables. Based on the results of Andersen and Dalgaard (2013) and Moyo (2013), the control variables selected include health level (*Health*), foreign trade (*Trade*), foreign direct investment (*FDI*), financial development (*Finance*), inflation (*Inflation*), government expenditure (*Expense*) and education level (*Education*). According to the healthy production theory, healthier level of labor force can increase the working hours, which has a significant positive impact on economic development (Shi and Hu, 2010). The mortality rate per thousand children under 5 years old is used as a proxy to represent the health level. A country's foreign trade reflects the opening level. A higher degree of openness represents a more convenient transnational production and bigger global trade market, which is conducive to the growth of the domestic economy. This paper uses the proportion of a country's total foreign trade to GDP to measure the country's foreign trade. Foreign direct investment has a significant contribution in stimulating the economic growth, absorbing employment, and expanding the scale of trade import and export (Liu and Xiong, 2016; Sunde, 2017). The proportion of net foreign direct investment inflows to GDP is devoted to control the role of foreign direct investment. Inflation is closely related to money supply and economic growth (Yi, 1995). All the monetary value has been price-adjusted using a country's CPI (consumer price index) annual growth rate based on 2015 to control the inflation impact. Government expenditure can promote economic growth by improving individual factor productivity (Romer, 1990), so this paper incorporates the proportion of government expenditure of GDP into the model. The education level of the labor force will affect the labor producing quality and then affect the economic output.

4. Results and discussions

4.1. The impacts of power outages on economic growth

Based on the econometric model, we estimate the impacts of power supply quality on economic growth, see Table 2. The regression results of mixed OLS (ordinary least square) estimator are listed in Column (1). The negative coefficient of the explanatory variable *lnSAIDI*is significant at the 10% level, indicates that the duration of the power outage encumbers the economic growth rate. After controlling the national fixed effect, shown in Column (2), the negative impact of the explanatory variable *lnSAIDI* on the explained variable *gGDP* increases, along with a growth in significance level from 10% to 1%. Column (3) presents the two-way fixed effect regression results with a year fixed effect added based on Column (2). It points out that every 1% increase in power outage duration will lead to a 0.99% decrease in the annual growth rate of a country's GDP, which is also significant at the 1% level. Due to the different economic shocks and impacts in different years, we believe that

Table 1
Descriptive statistics of variables.

Variable	Unit	Number	Average	Std	Min	Max
gGDP	%	760	1.534	5.175	−33.500	43.480
gGDPpc	%	760	1.537	2.648	−9.395	24.976
ln*SAIDI*	h	760	1.245	2.042	−4.605	7.763
ln*LD*	h	760	1.608	1.433	−2.659	7.541
DEA	%	760	2.212	1.521	0.000	8.840
TRA	%	760	62.883	36.021	0.000	208.477
FDI	%	760	4.503	63.165	−1275.190	972.700
CRE	%	760	55.504	43.224	0.000	217.641
CPI	%	760	3.169	7.401	−3.093	150.323
EXP	%	760	16.877	15.402	0.000	62.608
EDU	%	760	29.877	25.136	0.000	93.390

Note: Some missing observations were treated linearly interpolation.

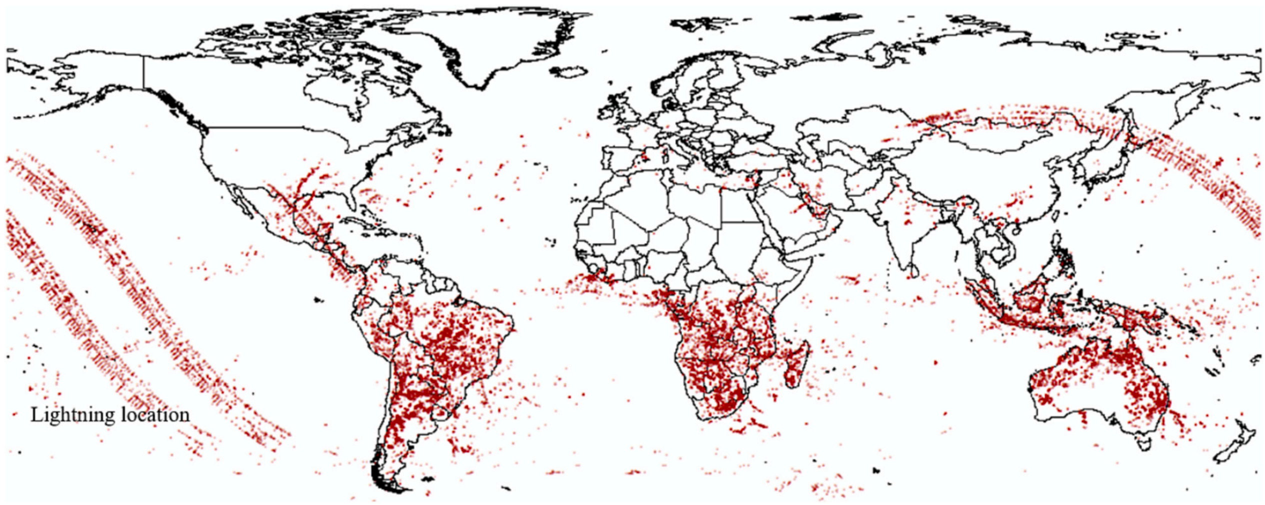

Fig. 2. Spatial distribution of lightning in the world in 2020.
Note: The red dots in the Figure indicate the lightning location from January 1 to January 31,2020, totally 56,154 times.

Table 2
Estimation results without considering endogenous effects.

Explanatory Variables	(1)	(2)	(3)
	Pool OLS	FE	FE
ln*SAIDI*	−0.325*	−1.147***	−0.992***
	(0.165)	(0.403)	(0.352)
FDI	0.000	0.001	0.001**
	(0.001)	(0.001)	(0.000)
CPI	−0.006	−0.038*	−0.009
	(0.023)	(0.021)	(0.024)
EXP	0.120***	0.207***	−0.022
	(0.014)	(0.018)	(0.035)
TRA	0.001	0.139***	0.078**
	(0.006)	(0.042)	(0.033)
DEA	0.676***	5.185***	−2.954*
	(0.223)	(1.835)	(1.545)
CRE	−0.010*	−0.025	−0.021
	(0.006)	(0.024)	(0.016)
Constant	−1.149	−19.350***	8.167*
	(0.867)	(5.518)	(4.894)
R^2	0.137	0.337	0.549
F statistics	12.39	38.53	40.19
National fixed effect	NO	YES	YES
Year fixed effect	NO	NO	YES
Observations	760	760	760

Note: In coefficient brackets, we show the standard deviation; ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively.

Table 3
Estimation results of instrumental variables regression.

Explanatory Variables	(1)	(2)	(3)
	IV	IV	IV
ln*SAIDI*	−0.815***	−2.538**	−2.156**
	(0.252)	(1.065)	(0.869)
FDI	0.001	0.001	0.001*
	(0.003)	(0.001)	(0.000)
CPI	0.001	−0.024	0.002
	(0.026)	(0.025)	(0.025)
EXP	0.128***	0.206***	−0.019
	(0.013)	(0.020)	(0.035)
TRA	−0.003	0.132**	0.075**
	(0.006)	(0.047)	(0.035)
DEA	0.962***	4.226*	−3.759**
	(0.200)	(1.893)	(1.851)
CRE	−0.016***	−0.024	−0.020
	(0.006)	(0.025)	(0.017)
Constant	−0.740	−15.227**	11.416*
	(0.721)	(6.408)	(5.930)
R^2	0.317	0.296	0.521
F statistic	123.15	562.82	239.62
Sargan test	0.00	0.00	0.00
National fixed effect	NO	YES	YES
Year fixed effect	NO	NO	YES
Observations	760	760	760

Note: In coefficient brackets, we show the Standard deviation; ***, ** and * represent significance levels of 1%, 5% and 10%, respectively.

the estimation results of the fixed effect of the year are more credible. Reliable power infrastructure can prevent enterprises and families from equipment damage and production interruption, thus promoting countries' economic development.

The coefficients of control variables shown in Table 2 are also in line with expectations. Foreign trade has a significant positive impact on economic growth, and the increase of a country's opening degree and international market participation can promote its faster economic growth. The level of health is closely related to economic growth. When both national and annual fixed effects are controlled, the economic growth rate will significantly increase by 2.95% if the mortality rate per 1000 children under 5 years of age in a country decreases by 1%. In addition, the increase in government expenditure and foreign direct investment can bring positive effects on national economic development, while the rise of inflation rate will bring a negative impact on the stable growth of a country's economy.

Next, we take the lightning density as an instrument variable to address endogenous problems. Table 3 reports the estimated results with an inclusion of the instrumental variable, which gradually controls the country-fixed effect and year-fixed effect from Column (1) to Column (3).[2] It can be seen that the coefficient of the explanatory variable *ln SAIDI* is still significantly negative, which verifies that unreliable power infrastructure does have a negative effect on a country's economic growth. Noticeably, the absolute value of the estimated coefficient of *ln*

[2] The rationality of instrumental variables is tested. First of all, in the two-stage least squares (2SLS) model, the F statistic of the first-stage regression is far above the empirical value of 10, and the minimum characteristic statistic of the test return of weak instrumental variables is 206.97, indicating that the selected instrumental variables are highly correlated with endogenous variables. The problem of 'weak instrumental variables' can be excluded. Secondly, the Sargan-Hansen test statistics reported in the over-identification test are not significant, and it is impossible to reject the null hypothesis that all variables are exogenous, which verifies that the selection of instrumental variables is effective.

SAIDI is significantly larger than the result in baseline regression in Table 2. In the case of controlling both the national fixed effect and the year fixed effect, every 1% increase in power outage duration will lead to a decrease in the real GDP growth rate by 2.16%. It also proves that the potential endogenous problems may make us underestimate the effects of the power infrastructure quality improvement on economic growth to a certain extent.

In addition, we have also compared the results estimated in this study with that from previous literature, see Table 4. The studies have adopted various proxy variables to indicate power supply quality, and focused on different aspects of output growth. Despite all this, our estimation is of the same sign with existing researches, making known that the negative effect on economic growth brought by power outage is consensual. Besides, with the similar IV approach, our estimator is close to the research done in Africa (Andersen and Dalgaard, 2013). The subtle differences between coefficients can be explained by sample range, for power outage in African countries may lead to stronger lash to economic growth than that in 152 countries.

4.2. Robustness analysis

This section analyzes the robustness of our estimated results from two aspects, including the replacement of the explanatory variables and the introduction of more control variables. The results are shown in Table 5. Columns (1)–(2) in Table 5 replace annual GDP growth rate with per capita GDP growth rate as the explanatory variable. Columns (3)–(4) add the education level of labor force to the basic model as control variable. Columns (5)–(7) introduce the secondary terms of government expenditure and foreign direct investment to the basic model.

In the replacement of explanatory variables, considering that some scholars have mentioned that the annual growth rate of real GDP per capita can be used to measure economic growth, we use the per capita GDP growth rate as the explained variable in regression, see Columns (1)–(2) of Table 5 (Andersen and Dalgaard, 2013; Straub and Hagiwara, 2010; Zheng et al., 2014). We can see that the negative impact of SAIDI on economic growth still exists. Moreover, if the fixed effects of country and year are both controlled, the annual growth rate of per capita GDP will significantly increase by 0.86% when the SAIDI decreases by 1%.

In the introduction of more control variables, the results when labor education level is controlled are reported in Columns (3)–(4) of Table 5, which are similar to those reported in Columns (2)–(3) of Table 3, respectively. This indicates that the estimated positive effect of improving the power infrastructure quality on economic growth is robust. Moreover, every 1% increase in the proportion of labor force with basic education will bring a 0.04% increase in economic growth, which passes the test at the 1% confidence level. In addition, previous studies have demonstrated an inverted U-shaped relationship between government expenditure, foreign direct investment, and economic growth (Romer, 1990; Sunde, 2017). Therefore, this study also introduces the quadratic term of government expenditure and foreign direct investment into the regression equation. In the results of columns (5)–(7) of Table 5, we can see that the regression coefficient of *lnSAIDI* is close to Column (3) in Table 3, which exhibits the robustness of our estimated results.

4.3. Heterogeneity analysis

This section will analyze the heterogeneity in the impacts of electricity infrastructure quality improvement on economic growth from three aspects, including different income levels, different land areas, and different electrification rates.

4.3.1. Income levels

To examine the variations in the impact of power supply quality on economic growth in countries with different income levels, we divide countries into low-income and high-income countries according to the classification method of the World Bank[3] and conduct instrumental variable regression on them respectively. According to the regressors in Table 6, the impact of power outage time on economic growth is significant in both types of countries. For every 1% reduction in the power outage duration, the economic growth in low-income countries will increase by 2.54%, while the economic growth in high-income countries will increase by 2.33%. This is because low-income countries are in the development stage of high dependence on electricity, and the normal operation of various industries is inseparable from a stable power supply. Therefore, unreliable power infrastructure caused by aging equipment, lack of maintenance, rapid expansion of power grids, and insufficient power generation capacity will cause greater economic losses (Hallegatte et al., 2019).

4.3.2. Land coverages

To measure the impact of power outages on economic growth in countries with different land areas, we divide 152 countries into the following five categories: small, medium, large, super-large and giant.[4] Table 7 shows the results of the heterogeneity analysis results of countries with different land areas. Overall, the negative effect of power outages on economic growth increases with land area size under 5 million square kilometers. For every 1% increase in the quality of power infrastructure, the improvement effect on the economic growth of small and medium-sized countries is <3%, while the economic growth effect of super-large countries is 7.10%. This is because the larger land area puts forward higher requirements for the reliability of the power system. Once the power infrastructure fails, it will spread to a wider range within large countries, resulting in more serious consequences. As for the six giant countries with a land area of >5 million square kilometers, the Russia, Canada, China, the United States, Brazil, and Australia, their large scales of energy infrastructure investment ensure the stability of power supply. The negative effect of power supply failure on economic growth is minimized due to the stronger reliability of power systems and the more complete power outage contingency plans.

4.3.3. Access rates to electricity

Access rates to electricity can reflect the development status and maturity grade of a country's electricity system. According to the World Bank, the access rates to electricity can be classified into three categories,[5] and the results of power outages on economic growth with different the access rates to electricity are shown in Table 8. We can see that the adverse impact of power outage duration on economic growth will be smaller if the access rates to electricity is higher. For every 1% increase in power outage duration, the negative effect is 7.71% in countries with the access rates to electricity <50%, while negative effect is only 2.07% in countries with the access rates to electricity higher than 90%. This is because countries with higher the access rates to electricity are more mature in their power systems, better able to cope with the consequences of power outages on economic activity and enable the use of backup power generation facilities to reduce their impact on economic development.

4.4. Policy impact simulations of reducing power outage duration

This section will conduct policy simulations to comprehensively

[3] Based on 2020, countries with per capita national income less than $4045 is defined as low-income. Countries with per capita national income above $4046 is defined as high-income. Classification criteria is from the World Bank https://www.worldbank.org.

[4] This classification comes from the World Bank , https://www.worldbank.org.

[5] The classification of electrification rates is from United Nations Development Program (UNDP) , https://www.undp.org/.

Table 4
Comparison with previous results.

Region	Year	Major Results	Methods	References
Africa	1995–2007	A 1% increase in the power outage frequency will lead to a 2.87% decrease in per capita GDP.	Instrumental Variable Approach	Andersen and Dalgaard (2013)
Rural Vietnam	2012–2016	If the number of days without power outage increases by 1%, the household income of livestock production and aquaculture activities will increase by about 8% and 11.6%, respectively.	Instrumental Variable Approach +Fixed Effect Method	Dang and La (2019)
India	2012	Increasing the power supply to 16 h per day will increase the total income of existing non-agricultural enterprises by about 0.1% of GDP.	Instrumental Variable Approach +PSM	Rao (2013)
102 developing countries	2010	An average increase of 1% in power generation capacity will increase the per capita growth rate by 0.22%.	Panel Fixed Effect Approach	Straub and Hagiwara (2010)

Table 5
Robustness test regression results.

Explanatory Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln*SAIDI*	−0.953**	−0.862**	−2.851*	−2.392**	−2.163**	−2.143**	−2.150**
	(0.397)	(0.364)	(1.469)	(1.198)	(0.870)	(0.882)	(0.884)
FDI			0.000	0.001*	−0.004**	0.001*	−0.004**
			(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
EXP			0.193***	−0.024	−0.020	0.008	0.006
			(0.022)	(0.036)	(0.035)	(0.095)	(0.006)
FDI^2					−0.000***		−0.000***
					(0.000)		(0.000)
EXP^2						−0.001	−0.001
						(0.002)	(0.002)
EDU			0.041**	0.006			
			(0.017)	(0.012)			
Control Variables	YES	YES	YES	YES	YES	YES	YES
Constant	YES	YES	YES	YES	YES	YES	YES
National fixed effect	YES	YES	YES	YES	YES	YES	YES
Year fixed effect	NO	YES	NO	YES	YES	YES	YES
Observations	760	760	760	760	760	760	760

Note: In coefficient brackets, we show the Standard deviation; ***, ** and * represent significance levels of 1%, 5% and 10%, respectively.

Table 6
Heterogeneity analysis of different income countries.

Explanatory Variables	(1)	(2)
	High-income countries	Low-income countries
lnSAIDI	−2.333***	−2.538***
	(0.720)	(0.582)
Control Variables	YES	YES
Constant	YES	YES
Number	104	48

Note: In coefficient brackets, we show the standard deviation; ***, ** and * represent significance levels of 1%, 5% and 10%, respectively.
For the lack of space, we don't directly show the difference estimation in this paper. If you are interested in it, please contact author

Table 7
Heterogeneity analysis of countries with different areas.

Explanatory Variables	(1)	(2)	(3)	(4)	(5)
	small <50 k km^2	medium 50-500 k km^2	large 500-1000 k km^2	super-large 100 k–5000 k km^2	giant >5000 k km^2
lnSAIDI	−2.382**	−2.494***	−3.084**	−7.100*	−1.167
	(1.480)	(0.666)	(1.335)	(3.783)	(0.936)
Control Variables	YES	YES	YES	YES	YES
Constant	YES	YES	YES	YES	YES
Number	52	60	15	19	6

Note: In coefficient brackets, we show the standard deviation; ***, ** and * represent significance levels of 1%, 5% and 10%, respectively.

Table 8
Heterogeneity analysis of countries with different access rates to electricity.

Explain Variables	(1)	(2)	(3)
	0%–50%	50%–90%	90%–100%
lnSAIDI	−7.713	−3.822***	−2.007***
	(7.044)	(1.083)	(0.764)
Control Variables	YES	YES	YES
Constant	YES	YES	YES
Number	13	17	122

Note: In coefficient brackets, we show the Standard deviation; ***, ** and * represent significance levels of 1%, 5% and 10%, respectively.

evaluate the impact of power supply quality improvement on the world economic growth and equity.

4.4.1. *Simulation of the gap between developing and developed countries*

Due to various technical and financial capacities, countries may improve their power infrastructure quality with different construction speed. It is of great concern that how will the expected reduction of power outage duration influence national economic development, especially the development gap between developing and developed countries.

Here we simulate future global SAIDI distribution based on its average descent speed in 2016–2020, shown in Fig. 3. Developing economies in Southeast Asia, South America and Africa have more potential in improving their power infrastructure reliability, compared with developed economies. This stimulates the aggregate GDP in developing economies increases by 10.52%, which is 1.68 percentage higher than that in developed economies (Fig. 4).

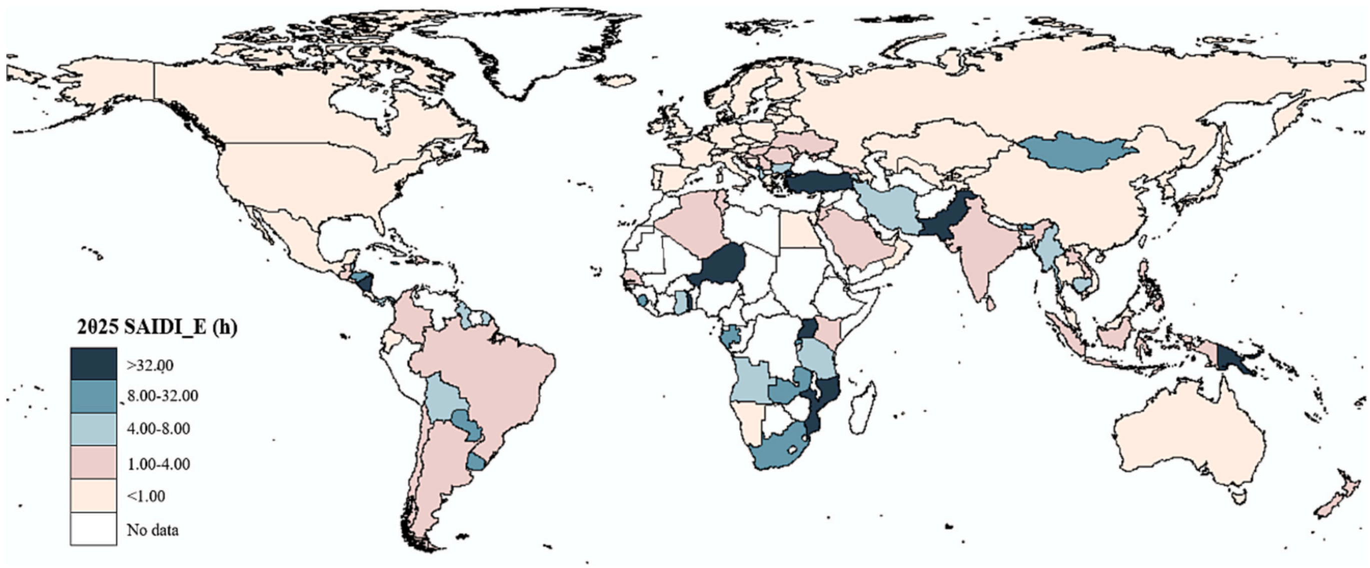

Fig. 3. Expected Global SAIDI in 2025.

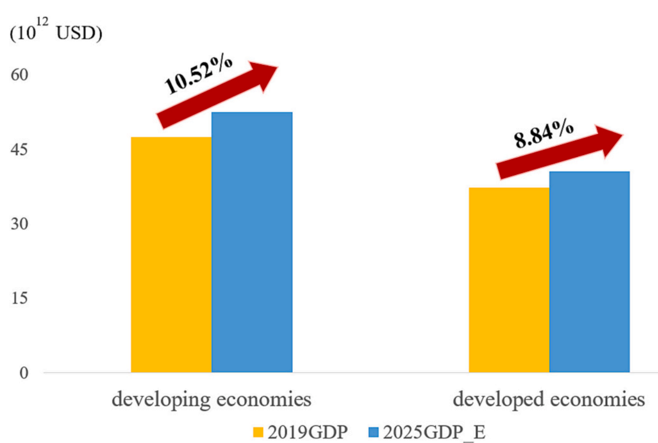

Fig. 4. GDP Growth in Developing and Developed Economies.
Note: Considering the impact of the COVID-19 in 2020 on the world economy, this paper uses 2019 data as a benchmark for calculation.

4.4.2. Simulation of power supply quality on economic equity

We assume a reduced power outage duration in 48 low-income countries. To conduct a sensitive analysis, ten scenarios have been set up. Scenario 1 is the baseline scenario, while Scenario 2 to Scenario 10 continuously reduce the mean SAIDI of low-income countries from 58.55 h to 0.32 h, indicating an increase in power infrastructure quality. The result estimated in income heterogeneity is applied to calculate he aggregate GDP growth and growth rate in ten scenarios. To measure economic equity, we draw Lorenz curves with population accumulation on the x-axis and GDP accumulation on the y-axis, and thus calculate the Gini coefficients of different scenarios. The results are shown in Fig. 5.

In Fig. 5, with the increase of power infrastructure quality improvement in low-income countries (from Scenario 2 to Scenario 10), the total world GDP and growth rate shows an increasing trend. If the power outage duration of low-income countries is set as 10% quantile of high-income countries, that is, its average SAIDI value drops to 0.32 h, it will increase the world's total GDP by about $421.9 billion, which is 4.98 ‰ higher than the current world economy. Among them, Asia and Africa contributed 71.94% and 22.31% respectively to this growth, far higher than the rest of the continent. This shows that improving the quality of power infrastructure can further stimulate the potential for world economic growth, especially in low-income countries in Asia and Africa. Increasing investment in power infrastructure construction and improving the quality of power supply can be greatly enhanced.

Additionally, the increase in power supply reliability in low-income countries will lead to the continuous decline of the GDP Gini coefficient. When the SAIDI value of low-income countries can be controlled at 0.32 h, the Gini coefficient of world GDP will decrease from 0.5994 to 0.5937 (a decrease of 9.55‰), indicating that improving the quality of power infrastructure can not only promote economic growth but also narrow the gap in economic development among countries in the world. This result verifies the contribution of power infrastructure to poverty reduction and equity promotion worldwide. It is proved to be necessary for World Organizations to invest in infrastructure construction in low-income countries. For example, the World Bank and the Global Fund for Disaster Reduction and Recovery (GFDRR) proposed to invest in building more resilient infrastructure in low- and middle-income countries.

5. Conclusions and policy implications

5.1. Conclusions

A stable and sustainable power supply is an important guarantee for promoting world economic growth. However, high reliability electricity system comes at cost, which requires new investment and improved maintenance. Therefore, a scientific understanding of how will power outages affect the world economy is crucial. This paper first analyzes the theoretical mechanism between power infrastructure quality improvement and economic growth. Then, we use the panel data of 152 countries from 2016 to 2020 to carry out empirical research, and annual lightning density of different countries is used as an instrumental variable to cope with potential endogenous problems. During this process, we have obtained the following major conclusions.

(1) **Improving the quality of power supply can significantly promote the economic growth in the world.** For every 1% reduction in the system average interruption duration time, the national economic growth rate will, on average, increase by 2.16%. Moreover, neglecting the potential endogenous problems will reduce the estimated results from 2.16% to 0.99%, which underestimates the effect of improving the power system reliability on a country's economic development.
(2) **The impact of power supply quality on economic growth shows significant heterogeneity with national**

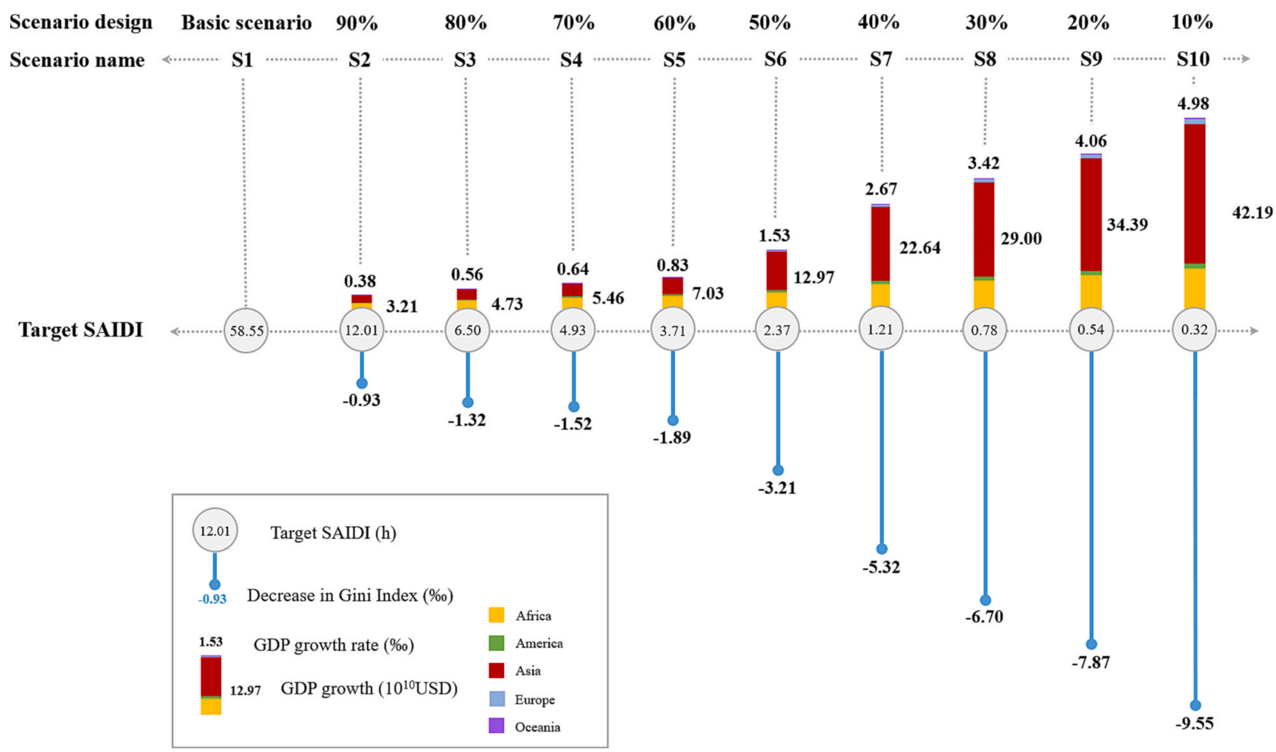

Fig. 5. Global GDP growth and GDP Gini coefficient changes under different scenarios.

Note: 1) The basic scenario and nine optimization scenarios are listed from left to right. S1 to S10 are the scenario names, and correspondingly 90%–10% is the scenario design. Taking the meaning of S10 (10%) as the example, this means the power outage duration of low-income countries is set as 10% quantile of high-income countries.

2) The mean of target SAIDI is marked in the center of the gray circle. The cumulative histogram above shows the growth of the world gross domestic product (GDP) in each scenario. We use different colors to distinguish the regional sources of GDP growth (North and South America are merged for simplicity) and show the volume and magnitude of GDP change at the left and top of the bar chart, respectively. The blue arrow below indicates the direction and magnitude of the GDP Gini coefficient worldwide.

3) Considering the impact of the COVID-19 in 2020 on the world economy, this paper uses 2019 data as a benchmark for calculation.

4) For low-income countries whose power infrastructure quality is higher than the corresponding high-income country supply quality quantile in each scenario, we do not change their SAIDI values.

characteristics. The impact of power supply quality improvement on economic growth in low-income countries is more obvious than that in high-income countries. A 1% reduction of power outage duration will increase economic growth by 2.54% in low-income countries, which is 0.23% higher than that in high-income countries. Moreover, the improvement of power supply quality, in general, has a greater impact on economic growth in countries with larger areas. For countries with land coverage between 100 and 500 km^2, the impact reaches to 7.10%. In addition, countries with lower electrification rates can benefit more from the power supply quality improvement. The economic benefit brought by power supply quality improvements is 4.33% larger in countries with lower electrification rates (<50%) than that in countries with lower electrification rates (>90%).

(3) **Improving the power supply quality in low-income countries will help to enhance the global economic development and fairness.** When the power supply quality of low-income countries increases to the 10% quantile of high-income countries, global GDP will increase by 4.98 ‰ ($421.9 billion) and global economic Gini coefficient will decrease by 9.55 ‰. This shows that improving the quality of power supply can not only promote economic growth but also narrow the gap between countries in different developing stage.

5.2. Policy implications

Based on the above results and conclusions, this study proposes several policy implications to better support the global economy development by improving the power supply quality.

Firstly, power outages, which represent for the quality of power infrastructure, have negative impact on national economic growth. As the power infrastructure investment continuously increase, we need to be more fully aware of the contribution brought by not only power supply quantity but also quality. Therefore, it is of great necessity to build a more reliable and available power infrastructure system to ensure the reliability of power supply. There are measurements can be employed, such as increasing the investment on establishing a reliable power system, optimizing the operation and maintenance. Detailly, ensuring safe and stable power supply should become the top concern of electricity supply system. We appeal for an expanded investment on improving the stability of power infrastructure, and attaching more importance to taking emergency measures when power outage occurs. Furthermore, it is recommended for countries to accelerate the construction of the national electricity market, in the purpose of promoting inter regional power transmission and market cooperation.

Secondly, inspired by heterogeneity analysis, power infrastructure construction of low-income countries, large land areas, and low electrification rate countries appear to be more efficient. However, most of these countries are suffering from unreliable power supply. This calls for poverty reduction assistances and global technology cooperation worldwide, to strengthen their resilience to natural disasters and accidents. Focusing on these three kinds of countries can reduce the additional economic costs caused by power supply interruption, thus promoting world economic growth.

At last, an improvement of power infrastructure quality in low-income countries has shown great potential to promote economic equality. It is essential to establish a complete power supply network to improve the reliability of power generation, transmission, and power consumption in low-income countries. Policies can be introduced to narrow the gap between the rich and the poor and achieve the goal of promoting fairness, including improving the infrastructure investment management and promoting the coverage of power infrastructure while ensuring the quality of power supply.

Although this paper has made some achievements in studying the impact of power supply quality on the economy, there are still some areas worth further improvements. Firstly, the time range of data can be expanded in the future to analyze the result heterogeneity at different stages. Secondly, the cost part of power supply quality improvement can be supplemented for cost-benefit analysis. These improvements will further enhance the understanding the effect of power supply quality on economic growth.

CRediT authorship contribution statement

Hao Chen: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Methodology. **Lu Jin:** Methodology, Writing – review & editing, Visualization. **Mingming Wang:** Software, Data curation. **Lin Guo:** Writing – review & editing. **Jingwen Wu:** Methodology, Writing – review & editing.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

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