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## Article

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# Energy infrastructure improvements have prompted inclusive growth in rural China

Bangzhu Zhu<sup>1, 2</sup>, Liqing Huang<sup>2</sup>, Yi-Ming Wei<sup>3</sup>, Lin Zhang<sup>4</sup>

**Abstract:** Stable energy supply with high quality infrastructure is vital for sustainable energy consumption and inclusive growth. In this paper, we develop empirical methods to evaluate the extent to what energy infrastructure improvement towards inclusive growth, which help guide policy development to achieve Sustainable Development Goals. By investigating the national-scale energy infrastructure improvement project in rural China, we identify the general and inclusive effect of income growth attributed to improved quality of energy infrastructure. The results show that energy infrastructure improvement contributes to rural income increase up to 69 Chinese renminbi (RMB) a year and narrows the income gap by 10 RMB for residents originally with an income difference of 100 RMB. The inclusive growth effect is pronounced in the eastern region, for the poor, for the educated, and becomes remarkable over time. Energy infrastructure improvement leads to income inclusive growth through abundant working time in the eastern and western regions, and general income growth in the middle region through individual health condition. Continuous efforts to energy infrastructure improvement and investments in education and work trainings, especially in the middle and western regions, are critical to achieve inclusive growth.

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## **Introduction**

Inclusive growth firstly introduced by the Asian Development Bank in 2007 aims at fairly and reasonably balancing economic growth and narrowing income distribution gap. Prompting inclusive and sustainable social community and economic growth is one of the most critical goals in the United Nation 2030 Sustainable Development Goals (SDGs)<sup>1</sup>. One challenge for achieving inclusive growth is energy poverty, defined by the International Energy Agency (IEA) as the conditions that people mainly utilize biomass energies (including fuelwood and bagasse) and other solid fuels for cooking and heating rather than using clean energies. Although household energy consumption accounts for a small proportion of total energy use of a country, it may generate dirty emissions and consequently lead to environmental damage and health risks<sup>2,3</sup>. Due to energy poverty, it is very likely that residents have to live in a poverty trap of air pollution, illness, reduced working competence, economic poverty and continuous usage of dirty energies<sup>4,5,6</sup>.

Numerous researches have indicated the general growth effect of energy infrastructure on economic and social development<sup>7,8,9</sup>, as the utilization of clean energies can greatly promote the growth of gross domestic product (GDP) and reduce CO<sub>2</sub> emission. Improved energy supply system can create a living environment more beneficial for residents to reach a higher level of income. However, most of the researches on energy supply are restricted on its general effects on national development<sup>10,11</sup>, resident income<sup>12,13</sup>, and firm production<sup>14,15,16</sup>. The role of energy infrastructure for inclusive development has received little attention. Besides, previous studies on inclusive growth focus on exploring the factors for promoting inclusive growth from the perspectives of regulatory policy, industrial structure, international trade, economic form, and technology innovation<sup>17,18,19</sup>. The explanation of the income

inclusive growth from the perspective of energy infrastructure improvement remains to be further investigated.

As the largest developing country, China also has faced a challenge to achieve inclusive growth. Per capita disposable income for urban Chinese (39250.8 RMB) is about three times larger than that of rural Chinese (14617 RMB) in 2018, implying a significant urban-rural gap in resident incomes<sup>20</sup>. China alone contributes to approximately 30% of global biomass fuels. A latest study shows that residential sector contributes 27% primary PM<sub>2.5</sub> in mainland China and about 80% residential emissions come from rural areas<sup>21</sup>. The quality of energy supply infrastructure in rural China has risen gradually over time. With energy infrastructure improvement, the distribution of clean energy by region has converged since 2000. However, the clean energy accessibility in the middle and western regions is lower than that in the eastern region (see supplementary data 1). Thus, clean energy accessibility and income inclusive growth in rural China are critical for the sake of global sustainable development and poverty elimination in terms of energy use and income. However, there is a lack of quantitative analysis on the interactions between energy infrastructure improvement and rural inclusive growth in China.

Although increased innovation<sup>23</sup>, education<sup>24,25,26,27</sup>, financial integration<sup>28</sup>, human capital<sup>29</sup>, unemployment<sup>30</sup>, institution<sup>31</sup> have been explored to be the reasons for income inequality and studies have revealed the relationship between energy consumption and economic growth<sup>32</sup>, we argue that income inclusive growth is derived from energy infrastructure improvement. We fill the gap by providing an empirical evidence to show that the provision of public infrastructure helps an economy to eliminate energy poverty and thus induce income growth at a micro level. Three major questions are addressed. Firstly, whether does energy infrastructure

improvement prompt inclusive growth and thus reduce income inequality between those with heterogeneous incomes, educations and work experiences? Secondly, how does income inclusive growth vary in the eastern, middle and western regions? Thirdly, what are the transmission mechanisms of inclusive growth? The results are essential for accelerating inclusive growth in regions with different levels of economic developments and resource endowments so as to help to design policies for sustainable and inclusive improvements.

To answer these questions, this paper provides a quantitative estimation of the effect of energy infrastructure improvement on inclusive growth and thus reduces income inequality. We extend the traditional Mincer model<sup>22</sup>, by clearly distinguishing between *general growth* effect and *inclusive growth* effect. The general growth effect refers to the increase in absolute income, and the inclusive growth effect indicates the decrease in income gap. By using a large-scale individual-level data obtained from the China Health and Nutrition Survey (CHNS), our empirical analysis finds that energy infrastructure improvement contributes to the increase in rural income growth and helps to narrow the rural income gap. The inclusive growth effect is more pronounced in the eastern region than that in the western region. Energy infrastructure improvements prompt income inclusive growth through abundant working time in the eastern and western regions. In the middle region, energy infrastructure improvement promotes income general growth through individual health condition. The poor and the educated can benefit more than their counterparts from energy infrastructure improvements.

## **Results**

**National inclusive estimation.** Table 1 reveals the inclusive growth effect from the national perspective. Model I shows that the coefficient of energy infrastructure

improvement is positive at a statistically significant level of 1%. That is, improving energy infrastructure has a positive effect on income growth. On average for the general growth, the incomes of rural residents increase up to 69 renminbi (RMB) a year. The coefficient of the interaction term is about -0.5, which implies that the inclusive growth effect of energy infrastructure improvement can narrow the income gap by 10 RMB for two residents originally with an income difference of 100 RMB. Thus, energy infrastructure improvement does not only enhance resident income but also narrow the gap of resident income and reduce rural inequality. The schooling year has a significantly positive correlation with incomes at the level of 1%, which is consistent with the results in the literature<sup>33,34,35,36</sup>.

Model II adds a set of personal features, including the interactions of energy infrastructure improvement with schooling year and with work experience. The coefficients of energy infrastructure improvement and  $Y_{t-1} \times E$  show a significant correlation with rural incomes at the level of 10%, which confirms the inclusive growth effect of energy infrastructure improvement for rural China. Similarly, we quantify that the general growth effect is about 23 RMB a year and the inclusive growth effect is about 8 RMB for people with 100 RMB income difference. The coefficients of  $sch \times E$  and  $exp \times E$  are significant at the 1% and 10% levels, respectively, which indicates that the educated and those with rich work experience benefit more from energy infrastructure improvement than their counterparts. It is worth noting that after introducing  $sch \times E$  and  $exp \times E$ , the coefficients of schooling year and work experience are no longer significant at the level of 10%. This suggests that the contributions of education and work experience to inclusive growth are based on energy infrastructure improvement.

**Table 1 The inclusive growth effects of energy infrastructure improvements on rural income**

|                              | Model I                | Model II              | Low-income group       | High-income group       |
|------------------------------|------------------------|-----------------------|------------------------|-------------------------|
| $Y_{t-1}$                    | 0.2299<br>(0.1622)     | 0.1374<br>(0.1826)    | 0.0596<br>(0.0403)     | 0.2761<br>( 0.2539 )    |
| $E$                          | 4.2328***<br>(1.3931)  | 3.1352*<br>(1.83)     | 3.5724*<br>(1.8901)    | 4.9734**<br>( 2.3536 )  |
| $Y_{t-1} \times E$           | -0.4925***<br>(0.1668) | -0.4427*<br>(0.2352)  | -0.3373*<br>(0.2018)   | -0.5523*<br>( 0.2985 )  |
| $sch \times E$               |                        | 0.0678***<br>(0.0199) | -0.0538<br>(0.0481)    | 0.016<br>( 0.0799 )     |
| $exp \times E$               |                        | 0.0068*<br>(0.0036)   | -0.0173<br>(0.0126)    | -0.0041<br>( 0.0163 )   |
| $sch$                        | 0.0484***<br>(0.0132)  | 0.0234<br>(0.0161)    | 0.03***<br>(0.0091)    | 0.0874<br>( 0.0784 )    |
| $exp$                        | 0.0157*<br>(0.0086)    | -0.0392<br>(0.0393)   | 0.0339***<br>(0.0057)  | 0.0078<br>( 0.015 )     |
| $qxp$                        | -0.0003***<br>(0.0001) | 0.0005<br>(0.0005)    | -0.0005***<br>(0.0001) | -0.00001<br>( 0.00008 ) |
| Additional control variables | Yes                    | Yes                   | Yes                    | Yes                     |
| Time effect                  | Yes                    | Yes                   | Yes                    | Yes                     |
| Overall growth effect        | >0                     | >0                    | >0                     | >0                      |
| $AR(1) - p$                  | 0                      | 0.001                 | 0                      | 0                       |
| $AR(2) - p$                  | 0.5                    | 0.771                 | 0.21                   | 0.569                   |
| $Hansen - p$                 | 0.134                  | 0.183                 | 0.888                  | 0.378                   |
| <i>Diff-in-Hansen GMM</i>    | 0.229                  | 0.12                  | 0.889                  | 0.311                   |
| <i>Diff-in-Hansen IV</i>     | 0.149                  | 0.1                   | 0.926                  | 0.313                   |
| Observations                 | 29050                  | 29050                 | 9729                   | 10260                   |

Note:  $E$  is energy infrastructure improvement.  $sch$  is individual schooling year.  $exp$  is individual work experience.  $qxp$  is quadratic individual work experience.  $Y_{t-1}$  is lagged logarithm of income.  $Y_{t-1} \times E$  is the interaction of lagged logarithm of income with energy infrastructure improvement.  $sch \times E$  is the interaction of individual schooling year with energy infrastructure improvement.  $exp \times E$  is the interaction

of individual work experience with energy infrastructure improvement. Robust standard error for each statistic is in parentheses. \*\*\*, \*\* and \* are significant at the 1%, 5% and 10% levels, respectively.

There exists a huge difference from rural resident incomes, with the minimum and maximum of 1.4354 RMB and 1967213 RMB respectively, showing a dramatic income inequality. By taking the mean of rural resident incomes in the sample as a critical point, we re-estimate the models for low-income and high-income groups in columns 4-5. The general growth effect is much stronger for high-income group (145 RMB) than low-income group (36 RMB). Rural energy infrastructure improvement exhibits inclusive growth effects for both low-income and high-income groups, which helps to narrow the income gaps of the high-income group by 13%, and of the low-income group by 5%. Moreover, we find that *sch* and *exp* are significant at the level of 1% for low-income group, which implies that to improve education and work experience of the poor enhances income inclusive growth.

**Regional inclusive estimation.** The results of the eastern, middle and western regions are reported in Table 2. It is found that the eastern region has higher levels of both general and inclusive growth effects than the western regions. In the eastern regions, rural income has been raised by 544 RMB a year. In terms of inclusiveness, energy infrastructure improvement helps to narrow down the income difference by 25%. The heterogeneous effect is marginal as the interactions of *E* with schooling year and with work experience are not significant at the level of 10%.

In the middle region, the general growth effect is significantly positive at the level of 10% and is about 20 RMB a year, while the inclusive effect is not significant at the level of 10%. Schooling year and work experience are statistically positive at the 5% and 1% levels, respectively, which indicates that improvements of energy infrastructure, education and work experience motivate income growth.

The general growth effect is about 10 RMB a year in the western region. Energy infrastructure improvement helps to narrow down the income difference by 2.2%. The heterogeneous effect is marginal as the interactions of energy infrastructure improvement with schooling year and with work experience are not significant at the level of 10%. However, schooling year and work experience are positive significant at the level of 1%.

| <b>Table 2 The regional inclusive growth effects of energy infrastructure improvements</b> |                       |                        |                        |
|--|-----------------------|------------------------|------------------------|
|  | <b>Eastern region</b> | <b>Middle region</b>   | <b>Western region</b>  |
| $Y_{t-1}$  | 0.57*<br>(0.3175)     | 0.0501<br>(0.1688)     | 0.1676***<br>(0.0407)  |
| $E$  | 6.3116**<br>(2.7108)  | 3.0148*<br>(1.708)     | 2.2702**<br>(1.0183)   |
| $Y_{t-1} \times E$   | -0.7432*<br>(0.3999)  | -0.0962<br>(0.2508)    | -0.1751*<br>(0.1023)   |
| $sch \times E$   | -0.0401<br>(0.1417)   | -0.1383<br>(0.1201)    | -0.0661<br>(0.0655)    |
| $exp \times E$   | 0.0066<br>(0.0286)    | -0.0425<br>(0.0275)    | -0.007<br>(0.0118)     |
| $sch$  | 0.2326<br>(0.162)     | 0.0986**<br>(0.0465)   | 0.0737***<br>(0.0231)  |
| $exp$  | 0.0199<br>(0.0294)    | 0.0423***<br>(0.0143)  | 0.037***<br>(0.0069)   |
| $qxp$  | 0.0001<br>(0.0001)    | -0.0005***<br>(0.0001) | -0.0006***<br>(0.0001) |
| Additional control variables   | Yes                   | Yes                    | Yes                    |
| Time effect  | Yes                   | Yes                    | Yes                    |
| Overall growth effect  | >0                    | >0                     | >0                     |
| $AR(1) - p$  | 0                     | 0.002                  | 0                      |
| $AR(2) - p$  | 0.185                 | 0.764                  | 0.111                  |
| $Hansen - p$   | 0.221                 | 0.306                  | 0.118                  |
| <i>Diff-in-Hansen GMM</i>  | 0.312                 | 0.155                  | 0.144                  |
| <i>Diff-in-Hansen IV</i>   | 0.107                 | 0.249                  | 0.1                    |
| Observations   | 10100                 | 10873                  | 8077                   |

**Mechanism analysis.** The mechanisms between income inclusive growth and energy infrastructure improvement are analyzed from the national and regional perspectives. Firstly, *BMI* and *Work* are not significant at the level of 10% in Table 3 (columns 2-3). The Sobel tests show that the mediating effects of *BMI* and *Work* are significant at the levels of 10% and 1%, respectively. In general, energy infrastructure improvement stimulates income inclusive growth through individual health condition and abundant working time. The interaction of energy infrastructure improvement with schooling year is significant at the level of 10%, which indicates that the better educated will benefit more from energy infrastructure improvement through *Work* than their counterparts.

The results of regional mechanism analyses are reported in Table 3 (columns 4-9). In the eastern region, *E* and  $Y_{t-1} \times E$  are significant at the levels of 5% and 10%, respectively. *BMI* is not significant at the level of 10%, and the Sobel test indicates that energy infrastructure improvement does not promote income inclusive growth through individual health condition. *Work* is significant at the level of 1%. The Sobel test shows that energy infrastructure improvement prompts income inclusive growth through abundant working time. In the middle region, *E* is significant at the level of 10%. *BMI* is not significant at the level of 10%. The Sobel test indicates that energy infrastructure improvement prompts resident income through individual health condition. However, *Work* is not significant at the level of 10%, and the Sobel test suggests that energy infrastructure improvement does not prompt resident income through abundant working time. Schooling year and work experience are significantly positive at the levels of 10% and 5%, respectively, which reveals that education and

work experience still play an essential role in the effects of energy infrastructure improvement on general income growth through individual health condition.

**Table 3 Mechanism analyses at national and regional levels**

|                              | National               |                        | Eastern region       |                       | Middle region          |                        | Western region        |                       |
|------------------------------|------------------------|------------------------|----------------------|-----------------------|------------------------|------------------------|-----------------------|-----------------------|
| $Y_{t-1}$                    | 0.1878<br>(0.1751)     | 0.2893<br>( 0.1773 )   | 0.5705<br>(0.3574)   | 0.4698*<br>(0.3078)   | 0.0628<br>(0.186)      | 0.0722<br>(0.1873)     | 0.174***<br>(0.0401)  | 0.1758***<br>(0.0422) |
| $E$                          | 3.7068**<br>( 1.6811 ) | 4.3***<br>( 1.5492 )   | 6.89**<br>(3.1015)   | 5.296**<br>(2.6476)   | 2.9792*<br>(1.7889)    | 2.9822*<br>(1.7771)    | 2.0849**<br>(0.9227)  | 2.2774**<br>(1.0522)  |
| $BMI$                        | 0.0225<br>(0.0561)     |                        | 0.0749<br>(0.0734)   |                       | -0.0068<br>(0.054)     |                        | 0.0442<br>(0.0608)    |                       |
| $Work$                       |                        | 0.0063<br>(0.0928)     |                      | 0.0882***<br>(0.0191) |                        | 0.0424<br>(0.1198)     |                       | -0.0418<br>(0.0986)   |
| $Y_{t-1} \times E$           | -0.4422*<br>(0.229)    | -0.67***<br>( 0.2273 ) | -0.8513*<br>(0.4511) | -0.6395*<br>(0.3558)  | -0.1654<br>(0.2885)    | -0.172<br>(0.2918)     | -0.2175**<br>(0.1022) | -0.1832*<br>(0.1044)  |
| $sch \times E$               | 0.0047<br>( 0.0985 )   | 0.12*<br>( 0.0648 )    | 0.0256<br>(0.1604)   | -0.0034<br>(0.1355)   | -0.1095<br>(0.1347)    | -0.1038<br>(0.1291)    | -0.0371<br>(0.0549)   | -0.0685<br>(0.0686)   |
| $exp \times E$               | 0.0003<br>( 0.0165 )   | 0.0205<br>( 0.0171 )   | 0.0037<br>(0.0309)   | 0.0021<br>(0.0203)    | -0.0266<br>(0.033)     | -0.0267<br>(0.0328)    | 0.002<br>(0.0107)     | -0.0048<br>(0.0125)   |
| $sch$                        | 0.1202<br>( 0.0998 )   | 0.0066<br>( 0.0262 )   | 0.2235<br>(0.1765)   | 0.2307<br>(0.1487)    | 0.0923*<br>(0.0502)    | 0.0903*<br>(0.0487)    | 0.0644***<br>(0.0211) | 0.0699***<br>(0.0242) |
| $exp$                        | 0.022<br>( 0.0174 )    | 0.0057<br>( 0.0112 )   | 0.0121<br>(0.0344)   | 0.0221<br>(0.0265)    | 0.0413**<br>(0.0163)   | 0.0406***<br>(0.0151)  | 0.025<br>(0.0227)     | 0.0391<br>(0.0243)    |
| $qxp$                        | -0.0002<br>( 0.0002 )  | -0.0002*<br>( 0.0001 ) | 0.0002<br>(0.0002)   | 0.0001<br>(0.0001)    | -0.0005***<br>(0.0001) | -0.0005***<br>(0.0001) | -0.0004<br>(0.0003)   | -0.0006*<br>(0.0004)  |
| Additional control variables | Yes                    | Yes                    | Yes                  | Yes                   | Yes                    | Yes                    | Yes                   | Yes                   |
| Time effect                  | Yes                    | Yes                    | Yes                  | Yes                   | Yes                    | Yes                    | Yes                   | Yes                   |
| Overall growth effect        | >0                     | >0                     | <0                   | >0                    | >0                     | >0                     | >0                    | >0                    |
| $AR(1) - p$                  | 0                      | 0                      | 0.001                | 0.001                 | 0.003                  | 0.003                  | 0                     | 0                     |
| $AR(2) - p$                  | 0.649                  | 0.453                  | 0.242                | 0.209                 | 0.768                  | 0.818                  | 0.129                 | 0.156                 |
| $Hansen - p$                 | 0.113                  | 0.192                  | 0.174                | 0.237                 | 0.22                   | 0.217                  | 0.121                 | 0.114                 |

|   |        |          |        |          |         |         |       |         |
|---|--------|----------|--------|----------|---------|---------|-------|---------|
| <i>Diff-in-Hansen</i><br><i>GMM</i>   | 0.11   | 0.201    | 0.427  | 0.426    | 0.103   | 0.111   | 0.178 | 0.237   |
| <i>Diff-in-Hansen</i><br><i>IV</i>  | 0.132  | 0.157    | 0.158  | 0.109    | 0.169   | 0.18    | 0.104 | 0.101   |
| Sobel test  | 1.852* | 2.745*** | 0.3268 | 2.969*** | 2.279** | -0.0016 | 1.392 | 2.061** |
| Observations  | 29050  | 29050    | 10100  | 10100    | 10873   | 10873   | 8077  | 8077    |
| Note: <i>BMI</i> is individual body mass index. <i>Work</i> is individual average days per week worked last year. |        |          |        |          |         |         |       |         |

In the western region,  $E$  is significant at the level of 5%.  $Y_{t-1} \times E$  is significant at the levels of 5% in column 8 and 10% in column 9. *BMI* is not significant at the level of 10% and the Sobel test indicates that energy infrastructure improvement does not prompt income inclusive growth through individual health condition. Although *Work* is not significant at the level of 10%, the Sobel test shows that energy infrastructure improvement prompts income inclusive growth through abundant working time. Schooling year is still significant at the level of 1% while work experience is not significant at the level of 10%, which suggests that schooling year plays a more important role than work experience when energy infrastructure improvement prompts income inclusive growth through abundant working time.

## Discussions

The results obtained at the national level reveal that energy infrastructure improvement promotes income inclusive growth in rural China. We also find that individual schooling year and work experience improve income more for low-income group than for high-income group, which indicates that promoting education development and skill training are crucial to income growth for low-income group. Meanwhile, energy infrastructure improvement prompts income inclusive growth through individual health condition and abundant working time. As alleviating energy poverty means providing efficient and safe energies for household energy consumption, energy infrastructure improvement decreases household cost, provides healthy living environment, increases household production efficiency, and

consequently stimulates income inclusive growth.

In the eastern region, energy infrastructure improvement promotes income inclusive growth, while individual schooling year and work experience are not. Moreover, energy infrastructure improvement prompts income inclusive growth through abundant working time. The possible reasons are that economy in the eastern region is developed rapidly and helps to attract talents. Although the energy infrastructure is relatively complete and clean fuels such as electricity and gas are available, the natural resource endowment is limited. Thus, energy infrastructure improvement prompts income inclusive growth more than education and work experience. Available clean fuels result in less indoor air pollution and health risks than dirty fuels. Energy infrastructure improvement does simulate the improvement of household efficiency, which enables rural resident to devote time on work resulting in income inclusive growth.

In the western region, energy infrastructure improvement, education and work experience contribute to income inclusive growth. That may be because western regions are short of human resources and economic development is at relatively low level. Therefore, energy infrastructure improvement, education and work experience help to enhance competitiveness and increase income inclusive growth. Compared to the eastern and middle regions, the economic development and resource exploitation in the western region are relatively limited. Household efficiency may allow resident to devote time and energy to work in order to stimulate local economic development and thus increases resident income.

In the middle region, energy infrastructure improvement, schooling year and work experience promote income general growth. The major resource endowment is coal and rural residents are short of clean energy. Residents may tend to use coal as fuel,

which easily results in serious air pollution and eventually affects their own health conditions. Consequently, poor health reduces work efficiency, and thus has negative impact on income general growth. Therefore, energy infrastructure improvement and increasing investment on education and work training may be useful measures for enhancing inclusive growth.

**Robustness analysis.** A set of robustness tests are conducted in this study, as shown in supplementary data 1.

The results of time consistency estimation are generally consistent with the results of Table 1. In different time frames, energy infrastructure improvement prompts resident incomes. The general and inclusive effects of energy infrastructure improvement increase over time.

The results on reverse causality analysis are consistent with those reported in Table 1. The interaction of schooling year with energy infrastructure improvement still has a positive effect on inclusive growth after a combination of macro-micro data.

The instrumental variable method is further used to address the endogeneity issue. The results confirm the existence of inclusive growth effect of energy infrastructure improvement. The inclusive effect between energy infrastructure improvement and resident income is robust.

The empirical findings show that improving energy infrastructure, with access to modern energy sources, contributes to promoting income growth and narrowing income gap. The contributions of education and work experience to inclusive income growth are based on energy infrastructure improvement. Moreover, we observe heterogeneous effects across different income groups and education levels. The poorer or the more educated can benefit more than their counterparts from energy infrastructure improvement. The transmission mechanisms vary in regions with

different levels of economic development and resource endowments. Several policy implications are derived for developing an inclusive society.

Firstly, continuous efforts should be provided for energy infrastructure improvement, in particular, to increase the penetration rate of access to modern energy sources for rural families. Other public services such as construction of hydropower and nuclear power station that contribute to the quality improvement of energy use shall be encouraged as well.

Secondly, the effects of education and work experience on inclusive growth of different income groups and regions are heterogeneous. Governments should increase investments in education and work training in rural areas, especially in the middle and western regions. A solution to rural income inequality is incomplete without the component of education.

Thirdly, as we have found the existence of regional heterogeneity, each region shall design its own appropriate policies tailored with the local characteristics. There is a huge difference on energy structure across regions. Therefore, it is necessary to take into consideration the regional resource endowment for the development planning. For the area with easy accessibility to clean fuels like the eastern China, it is essential to consider how to improve the utilization efficiency of energies further and reduce the cost of energies. Under exploited area like the western China shall focus more on the first access to electricity, liquefied natural gas, and natural gas. Inclusive growth in area with rich resource endowment of solid fuels like the middle China should enhance the access to electricity and natural gas while pay attention on resident health.

We acknowledge that the indicator measured energy infrastructure improvement includes only household cooking fuels. Besides, our mechanism analyses provide

limited information about the transmission mechanism between inclusive growth effect and energy infrastructure improvement.

Further research could measure energy infrastructure improvement from multi indicators in case of data availability. As the inclusive growth effect is only discussed between rural residents, it could further investigate the effect of energy infrastructure improvement on income inclusive growth between residents in urban and rural areas. We focus on the mediating effect in mechanism analyses. The further discussion on moderating effect would be valuable. Another area of future study is whether public infrastructures such as power station, public transportation and motorway prompt income inclusive growth.

Our quantitative results provide references and inspirations for inclusive development, which can be applied by national and regional policy-makers to identify the essential development areas. The proposed approach lays a foundation for estimating the inclusive growth effect of energy public provision. Moreover, the holistic analysis presented provides insights into the national and regional transmission mechanisms of energy infrastructure improvement aiming at improving income inclusive growth. This helps to obtain potential drivers of sustainable and inclusive growth, and consequently contributes to achieving SDGs.

## **Methods**

**Inclusive growth effect model.** This paper extends the traditional Mincer model<sup>22</sup> to quantitatively explore the effects of energy infrastructure improvement on income inclusive growth. Inclusiveness is defined as a narrower gap in resident income, compared to the previous year. Therefore, the proposed quantitative estimation is to investigate whether energy infrastructure can promote income growth, and at the same time, whether income gap can be narrowed between the rich and the poor. If the

answers to both questions are positive, we could conclude that energy infrastructure improvement indeed promotes inclusive growth.

$$Y_{it} = \alpha_0 + \alpha_1 E_{it} + \lambda C_{it} + \kappa_t + \mu_{it} \quad (1)$$

where,  $Y_{it}$  is the logarithm of income.  $E_{it}$  is energy infrastructure improvement. If energy infrastructure is improved, then it is recorded as 1, otherwise 0.  $C_{it}$  is control variable.  $\kappa_t$  and  $\mu_{it}$  are time fixed effect and random disturbance, respectively.

$\alpha_1$  shows the effect of energy infrastructure improvement on rural income.  $\alpha_1 > 0$  implies that energy infrastructure improvement has a positive effect on income, while  $\alpha_1 < 0$  shows that such improvement has a negative growth effect.

Eq. (1) fails to provide sufficient statistical evidence. We introduce a lagged term  $Y_{it-1}$ , and its interaction  $Y_{it-1} \times E_{it}$  into Eq. (1) to explore the inclusiveness of income growth.

$$Y_{it} = \alpha_0 + \alpha_1 E_{it} + \alpha_2 Y_{it-1} + \alpha_3 Y_{it-1} \times E_{it} + \lambda C_{it} + \kappa_t + \mu_{it} \quad (2)$$

The overall growth effect of  $E_{it}$  on  $Y_{it}$  is expressed as:

$$\frac{\partial Y_{it}}{\partial E_{it}} = \alpha_1 + \alpha_3 Y_{it-1} \quad (3)$$

$\alpha_3$  measures the inclusive effect on resident incomes. When  $\alpha_3 > 0$ , a higher income  $Y_{it-1}$  in the previous year leads to a larger growth benefit of income via  $E_{it}$ . A lower income in the previous year implies smaller benefit of income increase from  $E_{it}$ . As a whole, the income gap between the rich and the poor becomes larger. When  $\alpha_3 < 0$ ,  $\alpha_3 Y_{it-1}$  shows an income adjustment that avoids the enlargement of the income gap. On the conditions of  $\alpha_1 + \alpha_3 Y_{it-1} > 0$  and  $\alpha_3 < 0$ , energy infrastructure

improvement promotes the inclusive growth of  $Y_{it}$ . In other words, it can promote the overall  $Y_{it}$  on the one hand. On the other hand, it is possible to avoid the excessive growth of the income gap between predominant rural residents and other residents by conducting proper adjustment according to  $Y_{it-1}$ . In this way, rural income can steadily grow while sustaining or narrowing the income gap.

The endogeneity from reverse causal relationship between household income levels and the selections of modern energies may result in a biased estimation. Therefore, we apply the systematic generalized method of moments (GMM) proposed by Arellano and Bover<sup>37</sup> for the estimation of Eq. (2), which helps to provide an evidence on the causal relationship between energy infrastructure improvement and rural income growth. The inclusive growth effect of energy infrastructure improvement on rural income is estimated based on Eq. (2).

**Heterogeneous inclusive effect model.** In order to further explore the heterogeneous inclusive growth effect, we introduce the interactions of  $E_{it}$  with schooling year and with work experience into Eq. (2) to avoid potential omitted variable bias. Thus, Eq. (2) is expanded as:

$$Y_t = \alpha_0 + \alpha_1 E_{it} + \alpha_2 Y_{it-1} + \alpha_3 Y_{it-1} \times E_{it} + \alpha_4 sch_{it} \times E_{it} + \alpha_5 exp_{it} \times E_{it} + \lambda C_{it} + \kappa_t + \mu_{it} \quad (4)$$

Eq. (4) measures the effect of energy infrastructure improvement on inclusive growth of resident with different educational levels and work experiences, which is estimated by GMM method. The overall growth effect is measured by using the following Eq. (5).

$$\frac{\partial Y}{\partial E} = \underbrace{\alpha_1}_{\text{general effect}} + \underbrace{\alpha_3 Y_{it-1}}_{\text{inclusive effect}} + \underbrace{\alpha_4 sch_{it} + \alpha_5 exp_{it}}_{\text{heterogenous effect}} \quad (5)$$

**Mechanism analysis model.** Body mass index is a commonly used index to measure the proportion of weight to height, which reflects the individual health condition. We therefore introduce individual body mass index  $BMI$  and individual average days per week worked last year  $Work$  as the mediator variable  $M$  to analyze whether energy infrastructure improvement helps to increase income and to narrow the income gap through individual health condition and abundant working time. Eq. (6) measures to what extent energy infrastructure improvement prompts income growth through  $BMI$  and  $Work$ . Eq. (4) is extended to Eq. (7) to examine the transmission mechanisms from national and regional perspectives.

$$M_{it} = \delta_0 + \delta_1 E_{it} + \delta_2 M_{it-1} + \delta_3 sch_{it} \times E_{it} + \delta_4 exp_{it} \times E_{it} + \lambda C_{it} + \kappa_t + \mu_{it} \quad (6)$$

$$Y_t = \alpha_0 + \alpha_1 E_{it} + \alpha_2 Y_{it-1} + \alpha_3 Y_{it-1} \times E_{it} + \alpha_4 sch_{it} \times E_{it} + \alpha_5 exp_{it} \times E_{it} + \alpha_6 M_{it} + \lambda C_{it} + \kappa_t + \mu_{it} \quad (7)$$

**Time consistency estimation.** By dividing ten years in our sample into two time frames (1989~2011 and 1991~2015), robustness test is carried out on the two time frames. To avoid the inadequate instrumental variables in GMM regression, the two time frames are reduced the sample by one year. The time consistency estimation is conducted based on Eq. (4).

**Community level estimation.** To confirm that our results are not affected by the reverse causal problem, we use community level data for a complementary analysis. The mean of energy infrastructure improvement is calculated in the same community which is considered as the proxy variable of energy infrastructure improvement of a resident. The community level analysis is conducted based on Eq. (4).

**Endogenous effect estimation.** Rural resident using efficient and clean fuels for cooking such as electricity, liquefied natural gas, and natural gas, depends partly on the level of household income, which may cause endogenous problems. We further

use instrumental variable method to weaken this endogenous problem. The installed capacity of rural hydropower stations in each province  $Cap$  and whether rural residents have clean energy subsidy  $sub$  are obtained as the instrument variables of energy infrastructure improvement. The interaction terms  $Cap \times Y_{t-1}$ ,  $Cap \times sch$ ,  $Cap \times exp$  and  $sub \times sch$  are also used as the instrument variables of energy infrastructure improvement. The above indicators are conducted as instrument variables for the following considerations. Firstly, the power generation capacity of rural hydropower stations in each province is largely related to the power availability of local residents. The subsidies for clean energy reduce the pressure of residents to consume clean energy and encourage rural residents to use clean energy to a certain extent. Thus, the correlation hypothesis of instrument variables is satisfied. Secondly, the increase in installed capacity of rural hydropower stations in each province and clean energy subsidy last year can not directly affect rural resident income, which therefore meets the exogenous hypothesis. Eq. (4) is estimated by two-stage least square method (2SLS).

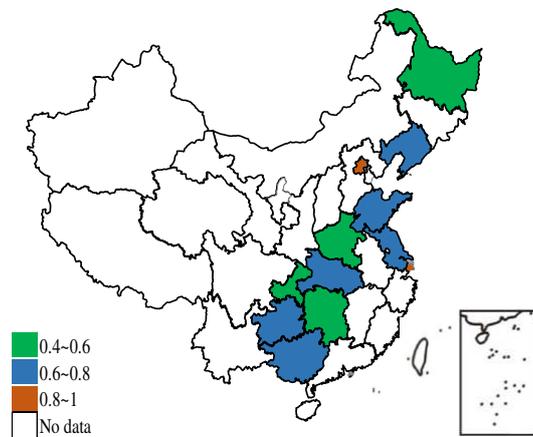
**Data description.** The data applied in the study is obtained from China Health and Nutrition Survey (CHNS) database. The data covers 49875 samples from a comprehensive investigation conducted in ten years (1989, 1991, 1993, 1997, 2000, 2004, 2006, 2009, 2011 and 2015) in 12 provinces, among which five (Liaoning, Beijing, Jiangsu, Shandong, Shanghai) are in the eastern China, four (Heilongjiang, Henan, Hubei, and Hunan) and three (Guizhou, Chongqing, and Guangxi) provinces are located in the middle and western China, respectively.<sup>2</sup> Individuals who are above

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<sup>2</sup> According to geographical location and economic development levels of China's regions, the National Bureau of Statistics of China defines the eastern, the middle and the western regions of Chinese mainland as: the eastern regions includes 11 provinces and cities (Beijing, Tianjin, and Shanghai municipalities, as well as Liaoning, Hebei, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan Provinces); the middle regions involves 8 provinces, including Shanxi, Jilin,

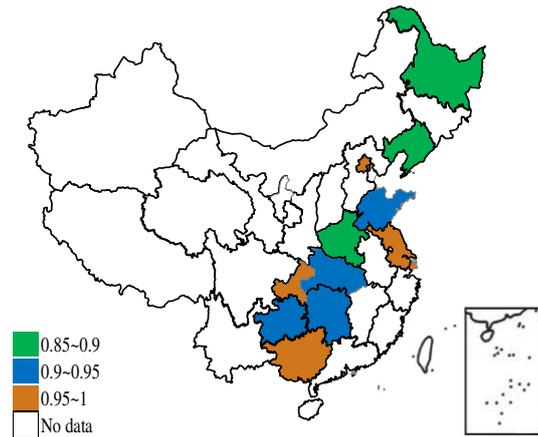
18 years old and work in rural areas are interviewed, and the logarithm of resident income at the constant price of 2015 is used as the explained variable.

The *Catalog of Polluting Fuels* issued by the Ministry of Environmental Protection of China in 2017 stipulates that polluting energy includes fuels that could burn directly for energy consumption such as raw coal, coal cinder and biomass fuels (including fuelwood, straw, and bagasse). If a respondent of a family uses efficient and clean fuels for cooking, including electricity, liquefied natural gas, and natural gas, the family is regarded as improved in terms of energy infrastructure. Our key variable energy infrastructure improvement indicator is recorded as 1. If the family member uses dirty energies (including fuelwood, charcoal, and briquette) for cooking, the family suffers from energy poverty, recorded as 0. Fig. 1 displays energy infrastructure improvement of different regions in 2011 and 2015.



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Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan Provinces; the western regions includes 12 provinces, cities and autonomous regions, including Inner Mongolia, Guangxi Zhuang Autonomous Region, Chongqing City, Sichuan Province, Guizhou Province, Yunnan Provinces, Tibet Autonomous Region, Shaanxi Province, Gansu Province, Qinghai Province, Ningxia Hui Autonomous Region and Xinjiang Uygur Autonomous Region.



**Fig. 1 Energy infrastructure improvement of rural China in 2011 and 2015.** The figures on the left and on the right describe the proportions of clean fuel availability of different regions in 2011 and 2015, respectively. The energy infrastructure improvement in rural China has risen gradually over time.

Control variables consist of individual schooling year, individual work experience and its quadratic term, accessibility to rural infrastructure, whether having a child or not and the location of the family<sup>38,39</sup>. Work experience cannot be measured directly. We follow Andrews and Buchinsky (2001) to calculate it as the years after normal schoolings. If we use “*sch*” to indicate the number years in schooling, and seven is the normal age to go to school, the individual work experience is thus  $\max(0, Age - sch - 7)$ <sup>40</sup>.

Rural infrastructure includes electric power, hydraulic engineering, and transportation. According to follow-up survey, the penetration rate of electric lighting in the sample reached more than 90% during 1989~2015, with no significant variations. Therefore, we use the accessibility to water-supply facilities as a proxy for the accessibility to rural infrastructure<sup>3</sup>.

**Data availability.** The input data of Fig. 1, the descriptive statistics of all the

<sup>3</sup> According to CHNS data, the proportions that rural residents utilize power lamps, kerosene, petroleum (fuel oil), candle and other energies for illumination during 1989~2015 reached 97.23%, 1.15%, 0.11%, 0.11% and 0.09%, respectively.

variables used in this study and the results of robustness tests are displayed in Supplementary Data 1. All the input data of the sample can be found in Supplementary Data 2.

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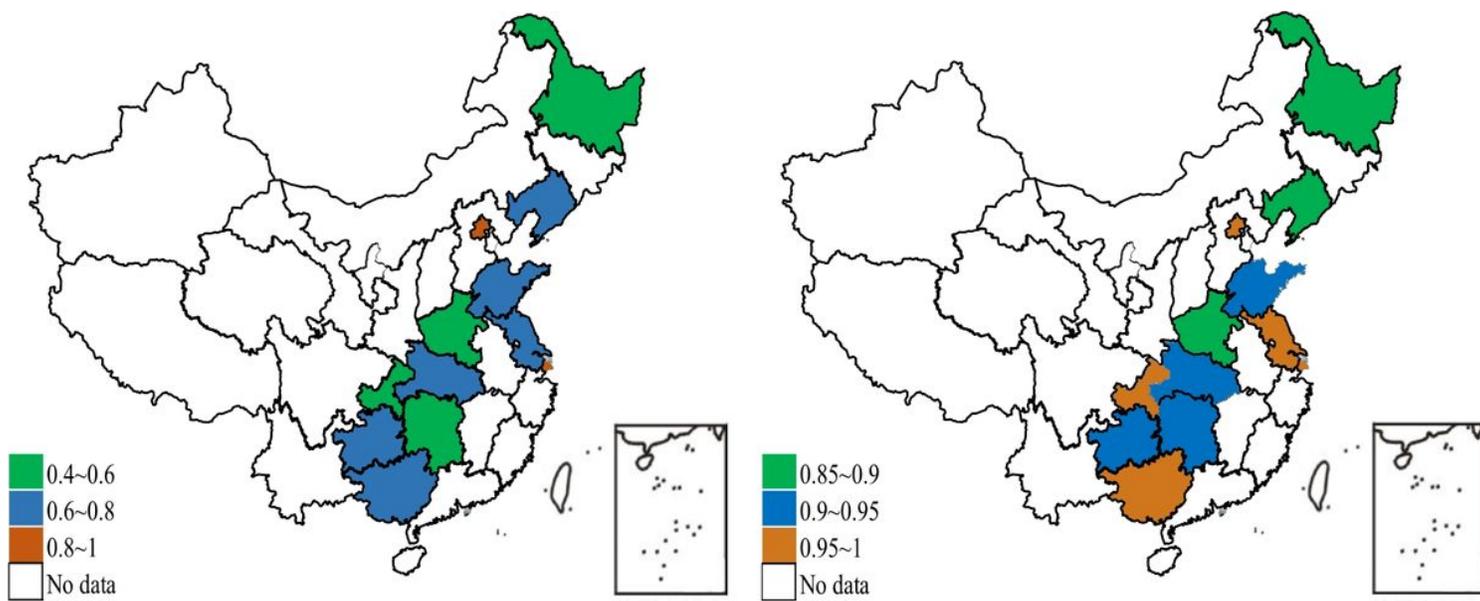
### **Author contributions**

B.Z. conceived the idea, designed study, analyzed results, and revised the draft. L.H. conducted all data compilation, processing, and calculations, and wrote the first draft. Y.W. provided comments on the draft. L.Z. contributed in writing and analyzing results.

### **Competing interests**

The authors declare no competing interests.

## Figures



**Figure 1**

Energy infrastructure improvement of rural China in 2011 and 2015. The figures on the left and on the right describe the proportions of clean fuel availability of different regions in 2011 and 2015, respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.