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# The analysis of solar energy investment, digital economy, and carbon emissions in China

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Solar energy supports sustainable economic growth by meeting the world's growing demand for energy while addressing climate change and reducing emissions. The literature focuses on the impact of solar energy on carbon emissions, but ignores the role of solar energy investment and the digital economy. This study investigates the influence of solar energy investment and digital economy on carbon emissions in China with the STIRPAT model. It uses the SYS-GMM method to empirically test the proposed hypotheses using provincial data for China from 2011 to 2019. The empirical results show that solar energy investment notably reduces carbon emissions. The moderating effect analysis shows that China's digital economy has a reverse moderating effect in the process of solar energy investment, affecting carbon emissions. The results of this research can be a useful contribution to the goal of carbon emission reduction in China, and relevant policy recommendations are proposed for the findings of this research. To reduce carbon emissions and help China reduce carbon emissions targets as soon as possible, more attention should be paid to solar energy investment. The rational use of the digital economy in investing in solar energy should be on the agenda.

KEYWORDS

**solar energy investment, carbon emissions, digital economy, STIRPAT model, moderation analysis**

## 1 Introduction

The finite nature of the world's resources and the pollution caused by non-renewable resources have prompted important thinking about global environmental issues. The role of renewable energy in the world has increased as instability around the world is exacerbated by pandemics. As countries' energy needs grow, so do energy security issues. This is true for members of the OECD and developing countries represented by China (Insel et al., 2022). In recent years, the energy crisis caused by COVID-19 and the war between Russia and Ukraine have directly affected the production, consumption, and energy supply of countries around the world. To the world, especially the developing countries, electricity demand is essential to economic recovery and to overcome the environmental problems caused by special weather. Fossil fuels, as traditional energy sources, have still occupied an important position in the production process of enterprises, but this leads to a large number of $CO_2$ emissions. Economic globalization has increased the economic and trade exchanges between countries, but at the same time, it has also brought about the problem of energy consumption. The development of economic globalization has improved the energy efficiency of middle-income countries (Liu et al., 2023). As a developing country, China has realized the importance of reducing non-renewable fossil energy consumption and improving energy

**TABLE 1 China's solar energy generation and proportion of total power generation.**

| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|
| Total electricity generation (kWh/yr) | 47,306 | 49,865 | 53,721 | 68,801 | 67,400 | 60,228 | 64,171 | 69,947 | 73,269 | 76,264 |
| Solar energy (kWh/yr) | 6 | 36 | 84 | 235 | 395 | 665 | 1,178 | 1769 | 2,237 | 2,611 |
| Solar energy (%) | 0.013 | 0.072 | 0.156 | 0.342 | 0.586 | 1.104 | 1.836 | 2.529 | 3.053 | 3.424 |

Note: Data collected from the China Electric Power Yearbook from 2011 to 2020.

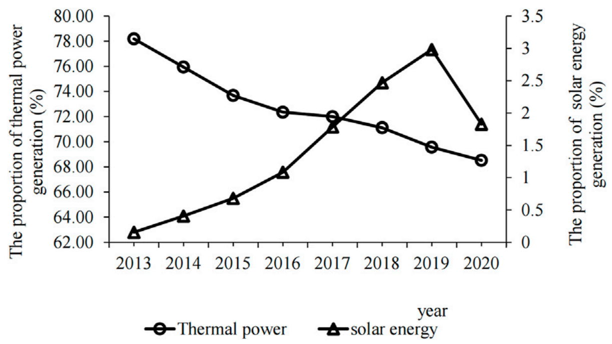

FIGURE 1
Proportion of thermal power and solar energy generation.

efficiency to reduce carbon emissions while doing its best to develop its economy and has actively applied it to macroeconomic policies. Therefore, the activities of economics, production, and living, such as corporate production and industrial structure, need to be overhauled. Reducing the reliance on non-renewable resources and switching to renewable energy sources, such as solar energy, is one of the most effective ways to achieve carbon emission reduction.

In spite of the high up-front costs and the lack of financing mechanisms, solar energy is well supported around the world. Solar energy can maintain sustainable economic growth by meeting the growing energy needs of the world while addressing climate change and reducing emissions (Yasmeen et al., 2022). In order to achieve the goal of "sustainable development," countries must continue to implement more energy efficiency policies and focus on solar energy research. Thus, increasing solar energy investment is a good solution. China's priority on solar energy is also reflected in the growing investment in solar energy and the gradual increase in the share of solar energy in total energy. Table 1 shows the share of China's use of solar power generation from 2011 to 2020, from 0.013% to 3.424%. Figure 1 shows the changes in the share of thermal power generation and solar power generation. It can be found that China is gradually using solar energy to replace traditional energy such as coal for power generation, and solar energy generation has gradually occupied an important position, thereby reducing the problems of environmental pollution and consumption of non-renewable energy caused by coal and other powers.

Through technological progress, we can develop new clean energy technologies such as solar, wind, and hydroelectric power to replace traditional fossil fuels as a method to reduce energy intensity and carbon emissions (Sun et al., 2021). The digital economy has reached a higher position in society and has become a new factor. As various digital technologies continue to develop and become more widespread, the size of the digital economy has also started to grow at a steady pace. Calculations by the China Academy of Information and Communication Research 2022 show that global digital spending will reach $1.5 trillion in 2021, an increase of 15% over the previous year. In the following 3 years (2022–2024), digital spending is expected to grow at an average rate of 17%, 6 points up over the previous 3 years. Against the backdrop of increasing digitalization trends, the use of digital economy in the development of new renewable energy sources must be emphasized. As the global digital economy continues to advance, the use of solar energy investment to reduce carbon emissions will contribute to the reduction of environmental problems and play an important role in improving the benefits for humans.

This leads us to the following questions: are solar energy investments effective in reducing carbon emissions? As an important component in examining a country's economic development today, the relevance of the digital economy should be taken into consideration. In addition, what is its role in the mechanism by which solar energy investment affects carbon emissions in China? The purpose of this paper is to answer the aforementioned questions. With China's emphasis on being a major global carbon emissions producer and its recent efforts to develop a digital economy and clean energy sources such as solar energy, there is still a research gap that places solar energy investment and the digital economy within the joint system of studying carbon emissions. The objective of this paper is to investigate how solar energy investments reduce carbon emissions, specifically through the digital economy. The paper aims to provide insights into the relationship between solar energy investments and carbon emissions at the province level and to explore the role of environmental policies and government institutions in promoting sustainability.

The research innovation and contribution of this paper are that we consider the vigorous development of carbon emissions. Most of the literature considers singular factor effects and one mechanism of contribution of solar energy investment to carbon emissions. To this end, this study expands the research ideas on the interactions among investments in solar energy and carbon emissions. Second, our findings on solar energy investment, the digital economy, and carbon emissions are useful reference points for policymakers and researchers alike. Third, the data on solar energy investment counted in previous China Electric Power Yearbooks are compiled to solve the data problem in the empirical analysis of solar energy investment. The contribution of this paper to the field is that it provides empirical evidence on the relationship between solar energy investments and carbon emissions. Additionally, this paper provides valuable insights into how carbon emissions can be reduced by investing in solar energy, which has important implications for policymakers and researchers in the field.

In summary, our main contribution is that solar energy will be the focus of clean energy development in China in the next decade due to rapidly declining costs. Therefore, the study of renewable energy investment and solar energy investment is crucial for planning, deciding, and developing effective energy policies. We chose 30 provinces in China as samples to study solar energy on carbon emissions, ensuring the integrity of all data and the accuracy of China's solar development research.

Our framework is as follows: Section 2 explains the literature and theoretical assumptions. Section 3 presents the research methodology for the STIRPAT model and moderation effect model of this study. Section 4 analyzes the empirical results. Finally, Section 5 elaborates on the conclusions and offers policy recommendations for the paper.

## 2 Literature review and the theoretical hypotheses

From a macro-national perspective, solar energy investment can directly reduce China's carbon emissions. It is well known that a country's production and economic activities require energy to sustain them and therefore contribute to $CO_2$ emissions. Today, solar energy is recognized as the largest reliable source of renewable energy. The energy generated by the Sun as a source of life in the world is highly valued. Worldwide carbon emissions have attained extreme proportions. Global environmental, economic, and even social problems can be caused by carbon emissions from fossil fuels such as oil, coal, and natural gas products (De Vries et al., 2007; International Energy Agency, 2012).

There is evidence from studies that investment in renewable energy can improve economic performance (Serezli et al., 2021; Wu, 2023). China follows a strategy named the "dual-carbon," aiming to reach carbon emissions peak by 2030 and carbon neutrality by 2060. China is by far the world's largest emitter of carbon dioxide, with the power sector accounting for approximately 50% of the overall $CO_2$ emissions in the country. It relies primarily on fossil fuels to cover its energy requirements for electricity generation and industrial production. According to data released by China's National Energy Administration, major power producers in China have invested 157.4 billion in solar energy construction-related projects in 2022, which represents an improvement of 326.7% compared to the previous year. On one hand, from a national policy perspective, investing in solar energy, a new renewable energy source, has important policy implications in achieving the double carbon target as soon as possible and getting rid of the dependence on traditional fossil-based non-renewable energy sources (Liargovas and Apostolopoulos, 2016; Insel et al., 2022; Mahbub et al., 2022; Zahoor et al., 2022). According to a Bloomberg NEF report, the demand for clean energy technologies has been on the rise since the continuing energy and climate crisis, with global investment in renewable energy reaching $226 billion in the first half of 2022. The worldwide focus on investing in solar energy projects is seen as global investment in new solar projects grew to $120 billion in the first half of 2022, 33% up from the first half of 2021, according to the Renewable Energy Investment Tracker for the second half of 2022 report. Solar energy is by far one of the most important renewable energy technologies and will continue to be so in the future. Solar energy resources may become more noticeable for electricity purposes despite rising investments in these energy resources (Hussain et al., 2023). Investment in solar renewable energy is an important driver of sustainable development, and therefore, solar energy investment is also very beneficial in decreasing the consumption of fossil fuels in China.

On the other hand, from an urban development perspective, the use and consumption of solar energy can ensure the country's economic development, address the increasingly pressing modern problem of energy poverty, and reduce $CO_2$ emissions and environmental pollution (Liargovas and Apostolopoulos, 2016; Insel et al., 2022; Zahoor et al., 2022). Carbon emissions reduced the flow of investment to green projects. Therefore, increasing the consumption of renewable energy and creating a carbon trading market are important for green finance policy improvement (Mngumi et al., 2022). In many parts of the world, energy poverty is an important issue that affects the development of human economic activities and the sustainability of the living environment. Many poor people in developing or underdeveloped countries still heavily rely on traditional energy sources. One solution to today's energy shortage is to use more clean energy, especially solar technology. It is a sign of poverty and the cause of environment pollution due to excessive reliance on inefficient traditional biomass fuels. Traditional energy sources like firewood lead to carbon emissions. The useful solution is to utilize clean energy such as solar technology. As a developing country, China should support the decarbonization of energy supply in developed countries to move from energy poverty to a low-carbon country and embark on a low-carbon development path (Güney, 2022). As a non-polluting energy source, solar energy will play a promising role as an alternative energy source in a future where reducing dependence on traditional fuels and addressing environmental issues are priorities. In recognition of the notable impact of energy on climate and pollution, the Chinese government has begun to support technologies that reduce emissions, especially solar energy, and has made a myriad of investments in solar energy to reduce greenhouse gas emissions by popularizing solar technology in poor rural areas and regions. Despite persistent cost inflation and supply chain resistance to development in recent years, China's demand for clean energy is growing by the day, and the global energy crisis has become the accelerator of the clean energy transition. In addition, as an emerging developing country, China has reached a certain level of industrial maturity and has recognized the environmental consequences of fossil fuels (Mahbub et al., 2022; Soomar et al., 2022; Yasmeen et al., 2022).

The massive infrastructure requirements of ICT for the development of the digital economy cause its indirect carbon emissions to far exceed its direct carbon reductions, which, through the rebound effect, leads to increased energy consumption and carbon emissions. The development of information technology has marginal benefits for all countries, which helps realize that technology and industrial development can ameliorate people's lives (Vu, 2011; Anser et al., 2021). It gives a new impetus to the digital economy, based on information technology, to enable intelligent management of the environment (Kjaer et al., 2018; Usman et al., 2021). An explosively growing line of research on carbon emissions studies a new paradigm of digital economy. On one hand, a widely agreed study argues that the development of information and communication technologies (ICTs) reduces energy consumption and carbon emissions (Ren et al., 2021). More specifically, digital economy has made it easier for residents to participate in environmental monitoring and compensate for the regulation (Granell et al., 2016). In addition, the development of the digital economy has led to the appearance of the digital divide and may increase income inequality, among other impacts (Quibria et al., 2003; Sorrell et al., 2009; Bauer, 2018; Zhou et al., 2019; Tewathia et al., 2020). On the basis of the foregoing analysis, we propose the following hypotheses.

**Hypothesis 1:** Solar energy investments can significantly affect and reduce carbon emissions.

**Hypothesis 2:** The digital economy has a moderating effect on the impact of investments in solar energy on the carbon emissions.

# 3 Methodology and data

## 3.1 Model construction

### 3.1.1 Benchmark model

In this section, we provide a more detailed description of the presented approach. The IPAT equation was first proposed to evaluate the influencing factors of environmental stress and developed into the algebraic equation of the IPAT model (Commoner, 2015). The model is meant to examine the influence of population (P), affluence (A), and technology (T) on the technical standard of production (Dietz and Rosa, 1997; Chertow, 2000; York et al., 2003).

$$I = P \cdot A \cdot T$$

The model explains the major drivers of environmental change. However, its main limitations are that the model cannot be tested for any hypothesis and the factors are linearly and monotonically related. As the prominent hurdle of the IPAT model, Dietz et al. extended the original model by proposing the STIRPAT nonlinear stochastic regression model, which regresses other drivers such as population, affluence, and technology to analyze the stochastic effects of drivers on changes in environmental stress (Dietz and Rosa, 1997; York et al., 2003). The STIRPAT model can be written as follows:

$$I_{it} = \alpha \cdot P_{it}^{\beta_1} \cdot A_{it}^{\beta_2} \cdot T_{it}^{\beta_3} \cdot e_{it}$$

α represents the constant coefficient of the model, $\beta_1, \beta_2, and\ \beta_3$ are the parameters to be estimated coefficients of the variables, *i* denotes the individual, and *t* denotes the time. When the parameter values are all equal to 1, the model becomes an IPAT constant equation. According to the study of York et al., it is concluded that taking both sides of the equation logarithmically does not change the nature of the data and the correlation between the variables, both from the model and data processing point of view. It reduces the covariance problem of the model and the heteroskedasticity problem, and it is more meaningful to observe each variable's impact on carbon emissions, so the equation can be transformed into the following:

$$\ln I_{it} = \alpha + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \varepsilon_{it}.$$

York et al. pointed out that the advantage of the STIRPAT model is that it allows the addition of other variables to analyze the non-proportional effect of that variable on environmental stress. The variables that are added must be conceptually identical to the multiplicative form that is given by the equation (York et al., 2003).

So far, many have used the STIRPAT model as a method to estimate the impact of $CO_2$ emissions. Based on previous scientific literature studies, we extended the theoretical STIRPAT model for this study to better serve our design requirements. The STIRPAT model is appropriately extended to include

$$C_{it} = \alpha \cdot SE_{it}^{\beta_1} \cdot P_{it}^{\beta_2} \cdot A_{it}^{\beta_3} \cdot T_{it}^{\beta_4} \cdot e_{it} \cdot X_{it}^{\beta_j}.$$

In the model, *i* refers to the province of China and t refers to the year. *C* represents carbon emissions; *SE* represents solar energy investment measured by solar energy production; *A* represents affluence measured by GDP *per capita*, *P* represents the population measured by the total population at the end of the year, *T* represents technology's proxy variable as the R&D expenditure of industrial enterprises, which is above the scale. *X* represents other control variables.

Applying the natural logarithms (*ln*) to both sides of the equation, the multiplication can be turned the model into addition. Elasticity coefficients can be used to analyze the effect of changing each driving force on the environment. We can have the following model:

$$\ln C_{it} = \alpha_0 + \beta_1 \ln SE_{it} + \beta_2 \ln P_{it} + \beta_3 \ln A_{it} + \beta_4 \ln T_{it} + \beta_j X_{it} + \varepsilon_{it}.$$

### 3.1.2 Moderation effect

In our analysis of the moderating effect of the digital economy on the influence of solar energy investment on carbon emissions, we construct the moderation model as follows:

$$\ln C_{it} = \alpha_0 + \beta_1 \ln SE_{it} + \beta_2 \ln P_{it} + \beta_3 \ln A_{it} + \beta_4 \ln T_{it} + \beta_5 \ln DE_{it} + \beta_6 \ln SE_{it} \times \ln DE_{it} + \beta_j X_{it} + \varepsilon_{it}.$$

*DE* is the digital economy. We add an interaction variable to examine the moderation effect of the digital economy on the influence of solar energy investment on carbon emissions. Because of the collinearity problem, model regression results have the probability of being biased. So we centralize the interaction variable.

Due to the past carbon emissions influencing the current carbon emissions, we consider the lag of carbon emissions as an indispensable variable to build a dynamic panel model. To solve this situation, we use the mainstream method, system generalized method of moments (SYS-GMM) estimators, as the dynamic GMM method. The dynamic GMM method was developed (Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bond, 1998). Among the GMM methods, System GMM is designed for situations with independent variables that are not strictly exogenous (Mileva, 2007). To achieve this goal, we use SYS-

**TABLE 2 Variable descriptions.**

| Variable | Description |
|---|---|
| Carbon emissions | Total apparent $CO_2$ emissions |
| lnSE | Provincial solar energy generation data |
| lnDE | Digital Economy Index |
| lnP | Total year-end population |
| lnA | GDP *per capita* |
| lnT | R&D expenditure of large-scale industrial enterprises |
| lni | Disposable income *per capita* |
| lncs | Level of urbanization |
| lnei | Investment in industrial pollution control |
| lnes | Rural electricity consumption *per capita* |
| lngov | Ratio of local government general budget expenditure to GDP |

**TABLE 3 Descriptive statistical results for the variables.**

| Variable | N | Mean | Std. dev | Min | Max |
|---|---|---|---|---|---|
| Carbon emissions | 270 | 9.945 | 1.586 | 4.271 | 11.952 |
| lnSE | 279 | 1.659 | 1.476 | 0.010 | 4.629 |
| lnDE | 245 | 0.196 | 0.112 | 0.024 | 0.610 |
| lnP | 279 | 8.127 | 0.843 | 5.762 | 9.404 |
| lnA | 279 | 10.745 | 0.432 | 9.849 | 11.925 |
| lnT | 270 | 14.280 | 1.341 | 11.123 | 16.863 |
| Lni | 279 | 9.918 | 0.409 | 9.056 | 11.070 |
| lncs | 279 | 0.450 | 0.083 | 0.215 | 0.637 |
| lnei | 278 | 11.830 | 1.196 | 7.018 | 13.911 |
| lnes | 279 | 5.793 | 0.915 | 3.557 | 8.321 |
| lngov | 279 | 0.250 | 0.134 | 0.113 | 0.829 |

GMM to estimate the model. The system GMM estimator is a method for estimating dynamic panel data models. It combines moment conditions for the model in first differences with moment conditions for the model in levels. For the STIRPAT model presented in the previous section, we finally use fixed regression estimation and system GMM regression estimation (Bun and Windmeijer, 2010).

## 3.2 Data

The explanatory variable is carbon emissions. According to previous studies, we chose the following indicators as the explanatory variables (Lin et al., 2009; Aguir Bargaoui et al., 2014; Shahbaz et al., 2016; Li et al., 2021; Wu et al., 2021). Table 2 shows the description of all variables.

We use the panel data on 30 provinces in China from 2011 to 2019. Data processing was performed for all variables, except for the index and share variables, which were logarithmically processed. Descriptive data are presented in Table 3.

The data on each variable in the model are from the following references: Carbon Emission Accounts and Datasets (CEADs), National Bureau of Statistics, and China Electric Power Yearbook (2011–2020). We use the entropy method to create the index of the digital economy (Li et al., 2021).

# 4 Empirical results

## 4.1 Direct impact of solar energy investment on carbon emissions

Given the short panel data characteristics of this paper and the possible endogeneity problems due to the lagged terms in the explanatory variables, the results of this paper are in line with the findings of the literature. The Hausman test was applied to choose the most appropriate model. The AR test was used to verify the appropriateness of the model settings, and the Hansen and Sargan tests were used to verify the validity of the instrumental variable settings. Based on the previous analysis, the direct effect of solar energy investment on carbon emissions is empirically tested, as shown in the following section, and the results are shown in Table 4.

The AR 1) test result is 0.054, and the AR 2) test result is 0.838, so it can be seen that there is first-order serial correlation and second-order serial uncorrelated residual terms of the model, and the model is reasonable. The Hansen and Sargan test results are 0.73 and 0.58, respectively, which indicates that there is no over-identification problem in the model and that there is no problem with weak instrumental variables.

As shown in regression results, the coefficient of elasticity of solar energy investment on carbon emissions is −0.023, which is significant at the 1% significance level. It suggests that for every 1% increase in solar energy investment, carbon emissions are reduced by 0.023%. Overall, China's investment in solar energy can reduce carbon emissions. Combining the aforementioned table with China's investment levels in solar energy over the years shows that China's investment in clean energy sources such as solar energy accounts for a relatively small percentage and that China is still investing mainly in traditional fossil energy sources. Reducing carbon emissions through investment in solar energy has a significant impact. Therefore, to reduce carbon emissions in the future, China should focus on solar energy investment as an important tool to reduce the reliance on non-renewable energy sources such as coal and fossil energy in the process of economic development. The analysis shows that reducing reliance on traditional fossil-based non-renewable energy sources and increasing investment in renewable energy sources, for instance, solar energy, are important ways to reduce carbon emissions.

We estimate the influence of solar energy investment on carbon emissions using the system GMM of a dynamic panel model that adds lagged one-period carbon emissions as an explanatory variable. The coefficient of solar energy investment is −0.043 and passes the significance test. For every 1% increase in solar energy investment, carbon emissions decrease by 0.043%. Population size, economic

**TABLE 4 Benchmark regression results.**

| Explanatory variable | (1) | (2) | (3) |
|---|---|---|---|
| | m1 | m2 | m3 |
| | OLS | | SYS GMM |
| lnSE | −0.023*** | −0.023*** | −0.043*** |
| | (0.004) | (0.006) | (0.012) |
| lnP | | 1.312** | 0.466*** |
| | | (0.420) | (0.119) |
| lnA | | −0.596** | 0.514*** |
| | | (0.253) | (0.193) |
| lnT | | 0.019 | −0.237* |
| | | (0.032) | (0.133) |
| lni | | −0.166 | −0.703 |
| | | (0.962) | (1.280) |
| lncs | | 3.237*** | 0.680** |
| | | (0.609) | (0.325) |
| lnei | | −0.021* | −0.088 |
| | | (0.011) | (0.079) |
| lnes | | −0.037 | −0.524 |
| | | (0.027) | (0.357) |
| lngov | | −0.203 | −0.592 |
| | | (0.184) | (1.233) |
| L.lnC | | | 1.210*** |
| | | | (0.159) |
| Constant | 9.917*** | 5.844 | −3.150** |
| | (0.003) | (3.486) | (1.417) |
| Observations | 270 | 270 | 240 |
| Year | Yes | Yes | Yes |
| Province | Yes | Yes | No |

Note: "*," "**," and "***" indicate significance at 10%, 5%, and 1%, respectively. Standard errors are shown in parentheses.

development, urbanization level, and carbon emissions show a positive relationship, and an increase in these variables leads to an increase in carbon emissions. Moreover, the current level of carbon emissions can be influenced by the carbon emissions in past periods, which indicates that carbon emissions have inertia. The increase in the resident population also represents the increase in local economic development, and the increase in urban population expands the size of the city, so the demand for electricity and energy is bound to have increased as well. The empirical results also confirm that solar energy investment is negatively correlated with carbon emissions and positively correlated with economic growth in China (Zahoor et al., 2022). For example, it suggests that policies such as urbanization and economic development have promoted economic growth at the expense of environmental sustainability. Therefore, from an urban development perspective, the use and consumption of solar energy can ensure the country's economic development, address the increasingly pressing problems of poverty in modern times, and reduce $CO_2$ emissions and environmental pollution. Therefore, hypothesis 1 is proved in the study.

## 4.2 Direct effect: heterogeneity of regional difference

Different regions in China have very different levels of economic development, different levels of factor endowments, and different levels and structures of industrial development. Therefore, we consider the division of three major regions of China into eastern, central, and western regions to further analyze the heterogeneous influence of solar energy investment on carbon

**TABLE 5 Direct effect results based on the heterogeneity of provinces in China.**

| Explanatory variable | (1) | (2) | (3) |
|---|---|---|---|
| | Eastern | Midland | Western |
| lnSE×dummy1 | −0.038*** | | |
| | (0.003) | | |
| lnSE×dummy2 | | −0.027*** | |
| | | (0.005) | |
| lnSE×dummy3 | | | −0.017*** |
| | | | (0.005) |
| lnP | 0.875** | 1.224*** | 1.174*** |
| | (0.268) | (0.198) | (0.249) |
| lnA | −0.510* | −0.579* | −0.622** |
| | (0.233) | (0.283) | (0.256) |
| lnT | 0.025 | 0.011 | 0.006 |
| | (0.047) | (0.045) | (0.044) |
| lni | 0.294* | 0.391** | 0.385** |
| | (0.131) | (0.159) | (0.142) |
| lncs | 2.844** | 2.287** | 2.941** |
| | (0.850) | (0.929) | (0.931) |
| lnei | −0.014** | −0.019** | −0.016** |
| | (0.006) | (0.007) | (0.005) |
| lnes | −0.028 | −0.051 | −0.025 |
| | (0.027) | (0.028) | (0.031) |
| lngov | −0.487 | −0.444 | −0.864** |
| | (0.276) | (0.370) | (0.277) |
| Constant | 4.168 | 1.713 | 2.340 |
| | (2.668) | (2.313) | (2.676) |
| Observations | 270 | 270 | 270 |
| Province | Yes | Yes | Yes |
| Year | No | No | No |

Note: "*," "**," and "***" indicate significance at 10%, 5%, and 1%, respectively. Standard errors are shown in parentheses.

emissions in different provinces of China. We depict the results in Table 5.

Three dummy variables are set separately and according to the model settings, if $i \in$ eastern region, then dummy 1 = 1; if $i \in$ central region, then dummy 2 = 1; and if $i \in$ western region, then dummy 3 = 1. Instead, the value is zero.

The coefficients of solar energy investment in the models of different regions are significantly negative, as is shown in Table 5, indicating that solar energy investment is effective in reducing carbon emissions in different regions. In the models, the coefficients of solar energy investment are −0.038, −0.027, and −0.017, respectively, which means that for every 1% increase in solar energy investment, carbon emissions in the three regions can be reduced by 0.038%, 0.027%, and 0.017%, respectively. It can be seen that the effect of solar energy investment on carbon emissions reduction is highest in the eastern region and lowest in the western region. In a nutshell, the eastern region is the most economically developed region in China, and the estimation results show that the more economically developed the region, the better the effect of solar energy investment on carbon emissions reduction.

## 4.3 Moderation effects of the digital economy on solar energy investment and carbon emissions

Based on the regression results of the model with the inclusion of the digital economy, as shown in Table 6, the coefficients of

**TABLE 6** Regression results of the moderating effect.

| Explanatory variable | (1) | (2) | (3) |
|---|---|---|---|
| | m1 | m2 | m3 |
| | OLS | | SYS GMM |
| lnSE | −0.025*** | −0.042*** | −0.040*** |
| | (0.002) | (0.008) | (0.006) |
| lnDE | 0.263* | −0.257 | −0.834** |
| | (0.128) | (0.248) | (0.396) |
| lnSE×lnDE | 0.048* | 0.100*** | 0.078*** |
| | (0.023) | (0.028) | (0.029) |
| lnP | | 1.258*** | 0.508 |
| | | (0.229) | (0.629) |
| lnA | | −0.339 | 0.238 |
| | | (0.315) | (0.864) |
| lnT | | 0.005 | −0.331 |
| | | (0.051) | (0.173)* |
| lni | | 0.183 | −1.191 |
| | | (0.148) | (1.281) |
| lncs | | 2.292** | 2.485*** |
| | | (0.829) | (0.147) |
| lnei | | −0.019** | 0.132 |
| | | (0.006) | (0.111) |
| lnes | | −0.052 | −0.453 |
| | | (0.033) | (0.199)** |
| lngov | | −0.324 | −0.056 |
| | | (0.347) | (1.179) |
| L.lnC | | | 1.197*** |
| | | | (0.200) |
| Constant | 9.922*** | 1.026 | 3.171 |
| | (0.020) | (2.974) | (6.187) |
| Observations | 268 | 268 | 238 |
| Year | Yes | Yes | Yes |
| Province | Yes | Yes | No |

Note: "*," "**," and "***" indicate significance at 10%, 5%, and 1%, respectively. Standard errors are shown in parentheses.

interaction terms of the digital economy and solar energy investment are all significantly positive, although solar energy investment significantly reduces carbon emissions. This suggests that the impact of solar energy investment on carbon emissions is strongly moderated by the digital economy. Table 6 shows that the digital economy reduces carbon emissions, but these studies mostly consider the connection between the two from static models.

Table 6 shows a reverse moderating effect of the digital economy on solar energy investment, affecting carbon emissions. It may be because the digital economy is an issue in the field of solar energy investment in China. For this reason, the foundation for the development of the digital economy in China is weak, and solar energy investment is representative of clean energy technology; the industry development is not perfect, and the combination with the digital economy tools still needs a process. The results in Table 6 show the possibility that the digital divide phenomenon has an effect on carbon emissions from investments in solar energy. In a nutshell, this study proves Hypothesis 2.

**TABLE 7 Moderating effect results based on the heterogeneity of provinces in China.**

| Explanatory variable | (1) | (2) | (3) |
|---|---|---|---|
| | Eastern | Central | Western |
| lnSE | −0.037*** | −0.048*** | −0.042*** |
| | (0.010) | (0.006) | (0.007) |
| lnDE | −0.260 | −0.241 | −0.234 |
| | (0.249) | (0.259) | (0.267) |
| lnSE×lnDE×dummy1 | 0.099** | | |
| | (0.029) | | |
| lnSE×lnDE×dummy2 | | 0.171*** | |
| | | (0.028) | |
| lnSE×lnDE×dummy3 | | | 0.107*** |
| | | | (0.022) |
| lnP | 1.094** | 1.467*** | 1.274*** |
| | (0.323) | (0.194) | (0.205) |
| lnA | −0.325 | −0.401 | −0.424 |
| | (0.303) | (0.359) | (0.363) |
| lnT | 0.016 | −0.008 | 0.007 |
| | (0.057) | (0.047) | (0.052) |
| lni | 0.155 | 0.240 | 0.226 |
| | (0.140) | (0.181) | (0.173) |
| lncs | 2.629** | 2.188** | 2.851** |
| | (0.965) | (0.819) | (1.075) |
| lnei | −0.019** | −0.019*** | −0.019** |
| | (0.006) | (0.005) | (0.006) |
| lnes | −0.045 | −0.053 | −0.038 |
| | (0.035) | (0.034) | (0.038) |
| lngov | −0.428 | −0.462 | −0.810 |
| | (0.388) | (0.398) | (0.549) |
| Constant | 2.171 | −0.316 | 1.122 |
| | (3.621) | (2.517) | (2.929) |
| Observations | 238 | 238 | 238 |
| Province | Yes | Yes | Yes |
| Year | No | No | No |

Note: "*," "**," and "***" indicate significance at 10%, 5%, and 1%, respectively. Standard errors are shown in parentheses.

## 4.4 Moderating effect: heterogeneity of regional differences

It has been shown that there are regional differences in the attractiveness of investing in solar energy across regions (Liargovas and Apostolopoulos, 2016). Table 7 shows that the cross-product coefficients of solar energy investment and digital economy in eastern, central, and western regions are all significantly positive at the 1% level, indicating that the digital economy has a significant moderating effect on the impact of solar energy investment on carbon emissions in all three regions. In addition, the impact of the digital economy is significantly larger in the central region than in the western and eastern regions. This may be due to the fact that the central region does not have a developed economy compared to provinces in other regions, and the implementation of the digital economy will significantly improve the economic development of provinces in the central region, which, in turn, will significantly increase carbon emissions. In addition, based on the same reason, the impact of the digital economy is larger in the western region than in the eastern region.

## 5 Conclusion and policy implications

By using the data on 30 provinces from 2011 to 2019 in China, this study uses the STIRPAT model and a moderating effect model based on the SYS-GMM method to comparatively analyze the effects of solar energy investment on carbon emissions in China under static and dynamic model regressions. The importance of the digital economy in moderating effect of solar energy on carbon emissions is also discussed. The main conclusions are as follows.

Investment in solar energy can have a meaningful impact on reducing carbon emissions. The digital economy has a moderating effect on the impact of solar energy investments on carbon emissions. Specifically, the digital economy has the digital divide phenomenon on the impact of solar energy investment on carbon emissions. There is regional heterogeneity in the impact of solar energy investment on carbon emissions, with significant variations in the economic development of the three regions in China.

In summary, we hope that this work brings us one step closer to acknowledging solar energy investment and carbon emissions. First, the use of solar energy as a renewable and clean energy source will effectively reduce the use of fuels such as coal to generate electricity, thereby reducing carbon emissions. Therefore, increased investment in solar energy is an effective alternative for China to effectively move away from its dependence on traditional non-renewable energy resources such as fossil fuels. China should increase the scale of solar investment. Only when solar investment grows rapidly can China's carbon emissions have a significant impact and emission reduction effect. Second, China should pay more attention to improving the structure of its new energy industry and implement a differentiated solar energy investment policy. The term "information and communication technologies" (ICTs) is used to describe the new information and communication technologies (NICs), which are based on digital knowledge and information, modern information networks, and the efficient use of ICTs to improve the efficiency and optimize the structure of the economy. The digital economy has received much attention from China's policymakers and market participants[1]. Due to the development of ICTs, digital economy has become a vital element of production, moving from a vision to a reality. Furthermore, solar energy investments in China are utilizing digital economy to reduce carbon emissions. This paper's empirical analysis shows that the reverse moderating effect of the digital economy on the process of solar energy investment affects carbon emissions. Therefore, it is essential not only to simply increase solar energy investment but also to improve application of the digital economy in the solar energy investment process and to narrow the digital economy development gap between regions. On the other hand, the government should play a greater role in solar energy investment, not only as the main body of investment involved in solar energy investment but also to promote the investment platform of the digital economy and effective integration with the new energy industry to eliminate the potential risks brought by the digital economy to solar energy investment, thereby reducing carbon emissions.

The reconsideration of this work is that there is still much to be determined in terms of understanding the complex relationship between solar energy investments and carbon emissions. Although this paper provides valuable insights into the topic, there are still many unanswered questions that require further research. Additionally, more research is needed to understand how solar energy investments can be effectively leveraged to reduce carbon emissions in different contexts. Overall, while this paper makes an important contribution to the field, there is still much work to be performed to fully understand the complex dynamics at play in solar energy investments. This study has the following limitations. First, this study analyzes short-panel data from China and therefore cannot evaluate the impact of solar investment on carbon emissions from a global or macro perspective of other countries, nor can it present the global or international impact of solar investment on carbon emissions. Second, this study uses data within a short period, and accurate data can only be updated to 2019 due to data availability and other reasons. It does not include the influence of COVID-19 on solar energy investment. In the future, we will collect panel data over a longer period and consider the impact of COVID-19 on carbon emissions and solar energy investment.

## Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: Carbon Emission Accounts and Datasets (CEADs) https://www.ceads.net/data/province/by_sectoral_accounting/Provincial?#1188 China Electric Power Yearbook (2011-2020) https://data.cnki.net/v3/trade/Yearbook/Single/N2022080097?zcode=Z025 National Bureau of Statistics http://www.stats.gov.cn/enGliSH/Statisticaldata/AnnualData/.

## Author contributions

XW and JS contributed to the conception and design of the study. XW performed the data proceeding. XW performed the statistical analysis and empirical analysis. XW wrote the first draft of the manuscript. XW and XZ wrote sections of the manuscript. XZ and JS reviewed and edited the manuscript. All authors contributed to manuscript revision, and read and approved the submitted version.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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[1] G20 Digital Economy Development and Cooperation Initiative adopted at 2016 G20 Hangzhou Summit'.

## Publisher's note

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