*sustainability*

MDPI

*Article*

# How Does Digital Finance Affect Energy Efficiency?—Characteristics, Mechanisms, and Spatial Effects

**Ya Wu [1], Yin Liu [1,*] and Minglong Zhang [2]**

[1] College of Economics, Jinan University, Guangzhou 510632, China
[2] College of Economics, Shenzhen University, Shenzhen 518060, China
* Correspondence: liuyin07@stu2020.jnu.edu.cn

**Abstract:** The boundaries of traditional financial services have been expanded by digital finance, which has boosted their effectiveness and quality while encouraging energy-efficient production and lifestyles, and also influencing energy efficiency. This connection between energy efficiency and digital finance is empirically investigated in this paper using panel data from 278 cities from 2011 to 2019. The main findings indicate that energy efficiency can be greatly increased via digital finance. Moreover, usage depth and digitalization level can improve energy efficiency while coverage inhibits it; developed digital finance regions, central regions, and resource-based cities have all seen improvements in energy efficiency. Furthermore, green technology innovation and R&D investment are mechanisms for digital finance that can improve energy efficiency. Finally, further research illustrates that digital finance can improve local energy efficiency while inhibiting neighboring areas' efficiency, though this effect is insignificant. This research provides additional impetus for a rise in energy efficiency due to the growth of digital finance.

**Keywords:** digital finance; energy efficiency; R&D investment; green technology innovation; the moderation effect

check for updates

**Citation:** Wu, Y.; Liu, Y.; Zhang, M. How Does Digital Finance Affect Energy Efficiency?—Characteristics, Mechanisms, and Spatial Effects. *Sustainability* **2023**, *15*, 7071. https://doi.org/10.3390/su15097071

Academic Editors: John Beirne and David G. Fernandez

Received: 19 February 2023
Revised: 20 April 2023
Accepted: 21 April 2023
Published: 23 April 2023



## 1. Introduction

China's economic development has accelerated since its reform and opening up, and the overall amount of energy consumed has increased. From 1979 to 2019, the average GDP growth rate was 9.4%, while energy consumption increased by 5.4% on average. For a long time, the fast-growing economy and the promotion of the industrialization process resulted in a significant increase in energy consumption. Extensive economic development and inefficient energy utilization became significant impediments to China's long-term development [1]. China is the nation with the least efficient use of energy in the Regional Comprehensive Economic Partnership [2], with significant regional differences [3]. Economic development has shifted to a high-quality development phase, and the extensive economic growth model no longer applies to its current economic development. It is imperative that nations transform into new drivers of economic growth, and improving energy efficiency is imperative. Improving energy efficiency requires not just environmental and industrial legislation but also a strong backing of financial services [4]. However, because of the distorted price of financial products and the unbalanced factor allocation structure in the traditional financial system, the financial limitations that confront small and medium-sized economic entities (SMEs) are serious. Without sustained financial support, innovation activities can be hindered, and energy efficiency is difficult to improve [5]. Therefore, financial innovation is required to support a rise in energy effectiveness.

Digital finance is a new financial model that combines traditional finance and digital technology. Using cutting-edge digital technologies involving the Internet, big data, and cloud computing, it gradually desalinates the boundaries between regions of financial institutions, accelerates the flow of financial elements, strengthens the role of financial rational resource allocation, and effectively compensates for the blind spots of traditional financial services [6]. An improvement in the external financing environment is conducive to maximizing the role of SMEs in technological innovation. This could further promote technology transfer and diffusion, make the social division of labor more specialized, improve the original mode of production, and reduce energy consumption. Simultaneously, the convergence effect, diffusion effect, correlation effect, and amplification effect of the integrated development of digital technology and traditional finance are becoming more significant, which not only contributes to local energy consumption reduction but also influences that of nearby areas [7,8]. The development of digital finance to improve the financing environment of SMEs also implies lowering credit conditions, which can lay a solid economic foundation for enterprises to expand their production scale, resulting in the consumption of fossil fuels [9]. Clearly, digital finance can reduce energy consumption by rationalizing resource allocation, promoting technological innovation and spillover, and providing a new method, but it can also encourage enterprises to expand their production scale, resulting in increased energy consumption [10,11]. Furthermore, the growth of interregional digital finance may have a spatial spillover effect, not just on the immediate area's energy efficiency but also on the surrounding areas.

According to previous research, we cannot judge whether digital finance can improve energy efficiency. There is no consensus on how digital finance influences energy efficiency or whether it has a spatial impact. Therefore, in this study, 278 cities' panel data from 2011 to 2019 were used to measure energy efficiency through a non-radial directional distance function (NDDF), a fixed effect model was utilized to investigate how digital finance could influence energy efficiency, the moderating effect model was used to identify its mechanism, and the spatial Durbin model explored its spatial effect. There were three marginal contributions. First, digital finance was incorporated into the analysis framework of energy efficiency, providing empirical evidence for the development of digital finance to break the dual constraints of "economic development" and "energy conservation and emission reduction". Second, green technology innovation and R&D investment were incorporated into the mechanism by which digital finance improved energy efficiency. Third, the empirical findings demonstrated that regional energy efficiency was increased by digital finance while having no positive impact on the energy efficiency of neighboring areas. The main objective of this study is to propose a realistic and appropriate path for China's economic development's "green transformation" by evaluating how the development of digital finance affects energy efficiency in terms of emissions reduction and energy conservation.

The remaining portions are laid out as follows: An overview of the literature pertinent to this paper is supplied in the second portion. The third portion presents the theoretical hypothesis. The fourth portion contains an empirical model and data sources. The fifth portion contains the empirical evidence, robustness and endogenous test, mechanism discussion, and heterogeneity analysis of the impact that digital finance has on energy efficiency. The sixth portion examines the spatial effect of digital finance on energy efficiency. The final section includes conclusions and policy implications.

## 2. Literature Review

### *2.1. Related Research on Energy Efficiency*

Using less energy to generate the same quantity of services and usable products can be referred to as energy efficiency [12]. There are two ways to quantify energy efficiency: single-factor energy efficiency and total-factor energy efficiency. Single-factor energy efficiency has limits in practical research since it treats energy consumption as the only input component and ignores other input factors such as labor and capital. Total-factor energy efficiency considers multiple input and output factors, which can overcome the deficiency of single-factor energy efficiency. Two approaches exist for measuring total-factor energy efficiency: nonparametric [13] and parametric [14]. The parameter method is represented by the stochastic frontier method (SFA) [15], which measures efficiency by setting the production function. If there is an error in the setting of the production function, the effectiveness of the efficiency calculation can be reduced [16]. Data envelopment analysis (DEA) with a nonparametric estimation method determines the production boundary by establishing a linear programming model without setting a production function and calculates the distance from each point to the boundary as the efficiency value [17]. The DEA method was divided into a non-radial model and a radial model according to whether the input factors and production factors changed in the same proportion [17,18]. To overcome the input and output slack in the radial model, [19] a slack measurement model (SBM) was proposed based on an unexpected output to improve the measurement accuracy. In addition, the EBM model [20], directional distance function [21], and non-radial directional distance function are also common methods for measuring energy efficiency [22].

Energy efficiency can be influenced by a few factors, and there are intricate relationships between them [23]. Energy is distributed significantly unevenly across industries in China, and because of ongoing energy exploitation and changes to the national energy structure, the country's energy production capacity is spatially and quickly concentrated. When industrial agglomeration is modest, encouraging it can increase energy efficiency. However, after a certain point, industrial clustering hinders energy efficiency [24]. By altering the industrial structure and encouraging internal productivity growth, energy efficiency can be considerably boosted in places with low levels of growth in the industry [25]. Additionally, the development of modern industrial structures can be encouraged with the help of financial instruments, which could result in an increase in energy efficiency [26]. In terms of technology, digital technologies can indirectly improve green energy efficiency by reducing resource mismatch [27,28]. At the policy level, in response to the new trend of market-oriented reforms, China has gradually explored the role of policy tools for energy conservation and emission reduction. By establishing an emission trading system, the level of marketization can be improved, perfecting the government–market relationship and enhancing the development of factor markets to cut energy usage per GDP unit, and improving the green total factor energy efficiency through green innovation [29]. In accordance with the strict guidelines of the "civilized city" policy, resource-based regions can reduce their energy consumption by investing more in new technological and scientific advances; this improvement in energy efficiency is especially significant [30,31].

### *2.2. Research on Digital Finance*

The economic and environmental ramifications of digital finance are emphasized in the published research. As for the economic benefits of digital finance, scholars have investigated two ways that digital financial services may stimulate innovative vitality: decreasing information asymmetry and compressing the price of transactions [32], enriching online payment methods to promote consumption [33], easing corporate financing constraints, improving regional innovation and opening up, and promoting high-quality economic development [34–36]. Digital finance can help listed firms produce more, and it can also encourage SMEs to start businesses and promote sustainable employment [32,37,38]. Digital finance has promoted high-quality economic development by eliminating enterprise funding constraints and increasing regional innovation and opening, and coordinating regional development by utilizing the essential characteristic of inclusive services to ensure that development achievements can be shared by the whole people [36]. At this stage, the coverage of digital finance has the most significant effect on promoting sustainable economic development [35]. Digital finance can promote household consumption by enhancing payment convenience and reducing future uncertainty, and cities with fewer assets, less disposable income, and less financial literacy experience can obtain a stronger promotion effect from digital finance [33].

Regarding how digital finance affects the environment, some scholars believe that, as a supplement to traditional finance, financial assistance for environmental optimization can be found in digital finance; however, some scholars also believe that the development of digital finance may lead to environmental degradation. The promotion of digital finance reduces the misallocation of financial resources, boosts the effectiveness of financial services, streamlines the industrial structure while fostering economic growth, reallocating capital from unprofitable to profitable sectors, modifying the pattern of energy consumption and utilization efficiency, and achieving the goal of reducing carbon emissions [39]. Additionally, digital finance may advance green technical advancement, expand the availability of green loans, and significantly reduce ecological footprints. The marginal effects of digital finance can be amplified by reducing the digital divide, lowering environmental restrictions, and strengthening the government's capability of digital governance. The environmental inclusiveness effect of digital finance facilitates a win–win situation of economic development and ecological conservation [40]. However, as digital finance relieves corporate funding pressures, the proportion of the manufacturing industry using traditional industrial methods rises, which causes $CO_2$ emissions to rise. That is, the impact of growth in digital finance is primarily represented by the increase in carbon emissions from an increased output value [41]. The absence of cooperation among local governments in the development of digital finance results in a "siphoning effect" on entrepreneurship, innovation, and consumption in the surrounding towns. As a result, the removal of pollution in the surrounding cities may be impeded [42]. For example, the synergistic effect of digital finance and green technology innovation promotes local $CO_2$ emission efficiency while inhibiting neighboring cities' $CO_2$ emission efficiency to some extent [43].

### *2.3. The Impact of Digital Finance on Energy Efficiency*

The impact of digital finance on energy efficiency is still being debated in academia. Some academics believe that digital finance could boost economic growth and, thus, increase energy consumption [44,45]. On the one hand, digital finance has broadened the financing channels of SMEs, which also means reducing the credit threshold to a certain extent, effectively solving the capital constraints of SMEs and low-income groups and laying a solid economic foundation for enterprises to expand production scale. Increased energy use results from expanding the production scale [9]. On the other hand, the expansion of digital infrastructure has been accelerated by an improvement in digitalization, promoting the emergence and application of many new information and communication equipment, promoting people's electrification consumption mode, and strengthening a dependence on energy demand [46]. To some extent, increased financial inclusion increases customers' purchasing power and the use of automobiles and air conditioners, which contributes to environmental stress [39].

However, other researchers have discovered that digital financing can boost energy efficiency. For example, ICT can promote the progress of production technology, enable financial development, improve energy efficiency, facilitate the achievement of energy saving and emission reduction goals, and ensure energy security [47]. The limitations of time and space can be overcome by digital technology, which also shortens the distances between locations. It can efficiently mobilize financial resources, encourage the movement, integration, and coordination of components between cities, and strengthen the connections between regional economic activity. This is helpful for enhancing the city's green total factor production and promoting the green development of neighboring areas [4]. Digital finance has the possibility to provide better financial conditions, assisting in upgrading the supply system of the local technology-intensive manufacturing industry and flexible competition, leveraging the green development of technology-intensive manufacturing in neighboring areas through a demonstration effect and financial model innovation, and assisting in reducing energy consumption [48]. By advancing green technology and modernizing industrial structures, digital finance can increase energy efficiency [49]. In the case of the poor development of credit and capital markets, digital finance has a greater stimulating effect on the improvement of energy efficiency [50]. However, digital finance lowers the entry barrier for financial services and increases the accessibility of financial resources, thus enabling more groups to engage in production and commercial activities, leading to major pollution and reducing the environment's overall factor productivity [51].

Previous research looked into how economic growth, industrial structure, technological advancement, financial growth, and policies affect energy efficiency, and there have been numerous studies on the economic effects of digital finance. Despite pioneering research on the energy-saving effect of digital finance, there are still areas that require further investigation. First, the current research on how digital finance affects energy efficiency is conducted at a provincial level and ignores the development of variations across cities to enrich the research in this field, and cities must be seen as research objects. Second, few studies have employed the moderation effect to study the mechanisms of digital finance and energy efficiency; thus, it needs to be further explored. Finally, from a spatial perspective, there have not been many studies that address how digital finance affects energy efficiency, and a more prominent feature of digital finance is that it can break through time and space constraints to provide financial services and promote the radiation and linkage of regional economic activities, from which it is necessary to explore the spatial characteristics.

## 3. Theoretical Mechanism and Hypotheses

### *3.1. The Impact of Digital Finance on Energy Efficiency*

The new financial paradigm, "digital finance", combines traditional finance with digital technology. It can not only optimize resource allocation and reduce energy consumption but also help cultivate an energy-saving consumption mode and promote energy efficiency. First, digital technology can broaden financial service coverage, which helps to diversify capital supply, meet capital demand, improve financial service effectiveness, entice traditional businesses to move their operations online, eliminate manual processes, condense physical outlets, drastically reduce original transaction costs and potential resource consumption, and promote energy efficiency. Second, with the help of big data, the Internet, artificial intelligence, and other digital tools, digital finance can improve data screening and processing capabilities, increasing the amount of information used in financial services, reducing moral hazards and the adverse selection of economic subjects during the investment and financing process, and increasing the capital market popularity of businesses that prioritize innovation and environmental protection. Businesses that adopt cutting-edge technology and cut their energy consumption benefit from capital investments in technological innovation and technological transformation projects with lower pollution emissions. Finally, digital finance can cultivate green consumption patterns and green lifestyles. The paperless transaction mode led by digital finance, such as mobile ticket purchases, electronic invoices, shared bicycles, ant forests, and other low-carbon consumption modes, not only helps to reduce resource consumption and breed environmentally friendly consumers but also connects personal environmental awareness with socially green actions, broadens general population participation in environmental protection and drives the public to proceed deep into energy conservation. This study suggests the following hypothesis in light of this analysis:

**Hypothesis 1.** *Digital finance can improve energy efficiency.*

### *3.2. Mechanisms of Digital Finance Influencing Energy Efficiency*

#### 3.2.1. Digital Finance, Green Technology Innovation and Energy Efficiency

The fusion of green technological innovation and digital finance may be advantageous for energy efficiency. Green technology innovation attempts to enhance the energy efficiency, reduce the environmental load, and consider economic and environmental benefits. Green technology innovation needs green finance to provide financial support and platform support. Due to cost and risk problems, the service scope of green financial institutions has not yet covered many SMEs, which limits the role of green finance in financial services. Digital finance technologies spread to green financial institutions, widen user scenarios, and expand the radiation of green financial services, guiding the flow of green financial resources to green industries and environmentally friendly businesses. After enjoying convenient financing services, green and environmental protection enterprises can further increase the research and development of green technologies and more firmly adopt green and environmental protection production processes and processes, to reduce energy consumption. Meanwhile, with the help of funds, other businesses have made significant progress in modifying the traditional production model, which has improved the supply and value chains of established industries, increased the operational effectiveness of industrial organizations, and compelled low-end, backward industries to modernize [43], optimizing resource allocation, bringing efficiency and kinetic energy changes through the release of structural dividends, and ultimately promoting the improvement of energy efficiency [4]. This study makes the following suggestion in light of the preceding analysis:

**Hypothesis 2.1.** *The synergy of digital finance and green technology innovation enhances energy efficiency.*

3.2.2. Digital Finance, R&D Investment, and Energy Efficiency

The integration of digital finance and R&D investment is beneficial to increasing energy efficiency. R&D investment entails a high capital requirement, a long investment duration, and uncertain income. As a result, SMEs are vulnerable to the challenge of insufficient funds when undertaking technology research. Digital finance uses information technology to bring the long tail group into the service object, with the help of intelligent investment consulting, supply chain finance, consumer finance, and other ways to realize the effective collection of funds, expand the source of funds, and relaxing restrictions on enterprise R&D investment [50], which can help enterprises pay attention to improving production processes and technologies, reducing resource consumption and improving energy efficiency. Moreover, R&D investment is closely related to the development strategy of enterprises, involving the future business layout and development direction, and is regarded as a kind of important business secret. Enterprises are cautious when publishing information about R&D investment and frequently avoid disclosing relevant details, resulting in information asymmetry between enterprises and financial market investors and exacerbating enterprises' external financing constraints. The expansion of digital finance improves information accuracy and transparency, facilitates external investors' understanding of critical information, creates effective and reasonable external oversights, encourages enterprises to invest more in R&D, effectively improves production technology, and reduces energy consumption. Digital finance can make up for a lack of government financial support, providing external financing for enterprises, helping enterprises to continuously update production technology, and improving energy efficiency. Based on the preceding analysis, the following hypothesis was proposed:

**Hypothesis 2.2.** *The synergy of digital finance and R&D investment improves energy efficiency.*

*3.3. Spatial Effect of Digital Finance on Energy Efficiency*

The "trickle-down effect" of digital finance continues to spread to surrounding regions, creating a spillover impact. The spatial spillover effect of digital finance strengthens financial support and information exchange between regions, implying that the development of digital finance not only promotes the region's energy efficiency but also has a "demonstration effect" on the energy efficiency of neighboring areas, causing economic activity subjects in neighboring areas to take similar action. Therefore, digital finance not only promotes regional energy efficiency but can also have a spatial spillover effect on the energy efficiency of neighboring areas [39]. However, the growth of local digital finance has a "siphon effect" on the factors of production in neighboring areas, which is neither beneficial to capital accumulation nor technological innovation nor to reducing energy consumption [43]. Due to long-standing administrative divisions, local governments have developed digital finance in their own unique ways. This lack of overall coordination exacerbates the spatial self-selection effect of capital, technology, and talents, which leads to the indirect loss of long-term and overall benefits based on the maximization of their own interests and the potential risk of "beggar thy neighbor" in the impact of digital finance on energy efficiency. Consequently, digital finance can have a negative impact on the energy efficiency of neighboring areas [42].

**Hypothesis 3.** *The impact of digital finance on energy efficiency may have a spatial effect.*

Figure 1 illustrates the mechanisms by which digital finance affects energy efficiency.

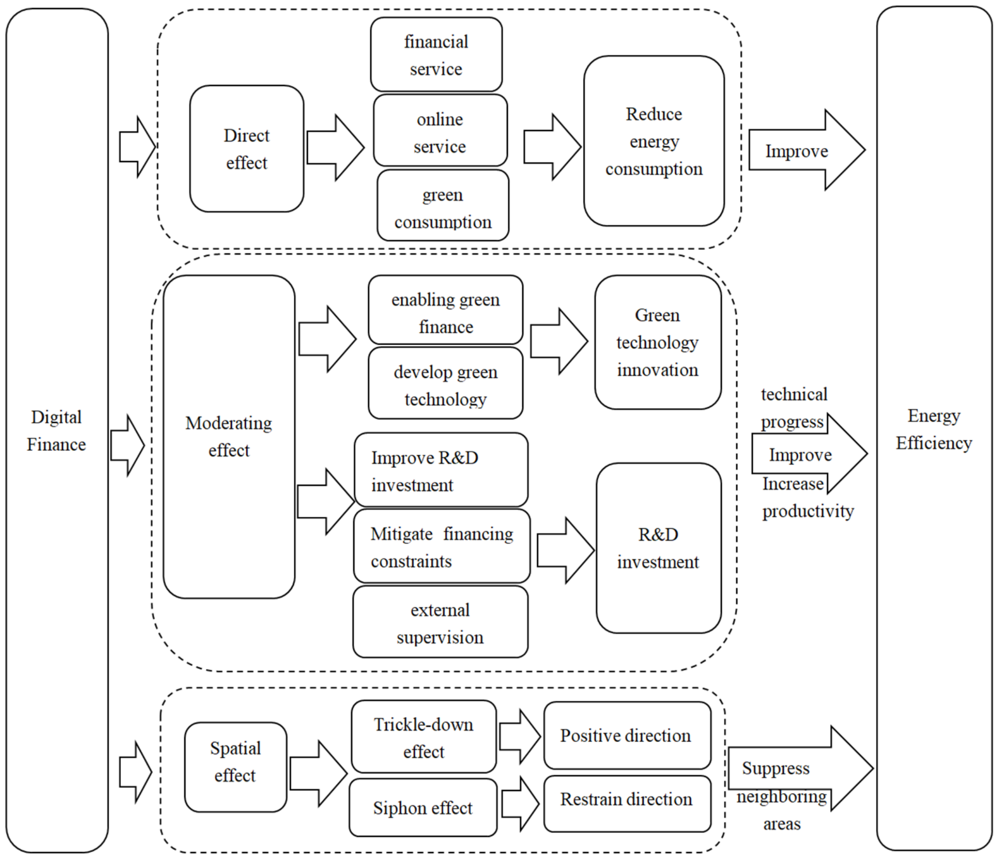


**Figure 1.** Mechanism of the impact of digital finance on energy efficiency.

## 4. Research Methods and Variable Description

### *4.1. Evaluation of Energy Efficiency*

After defining the environmental production technology function, the Data Envelopment Analysis (DEA) method was employed to assess energy efficiency. Each city can be considered a decision-making unit (DMU), and each DMU can be used as input variables for capital stock $(k)$, labor force $(l)$ and energy consumption $(e)$. In terms of accessibility and accuracy, data on coal, oil, and natural gas are not readily available at city levels, whereas electricity consumption is extensive and precise. Thus, the energy input data in this paper were measured using city electricity consumption [31]. The expected output gross regional product is represented by $(y)$ alongside the unexpected output of industrial sulfur dioxide $(s)$, industrial dust $(d)$, and industrial wastewater $(w)$. $P$ stands for production technology, which can be described as follows:

$$P = \{(k, l, e, y, s, d, w) : (k, l, e) \; can \; produce \; (y, s, d, w)\} \quad (1)$$

As for $P$, it ought to satisfy the null-jointness and weak resolvability hypotheses [52]. According to the weak resolvability hypothesis, lowering an undesirable output necessitates lowering a desirable output. The null-jointness hypothesis means that the only way to eliminate an undesirable output is to eliminate desirable output. The production function for this is:

$$P = \left\{ \begin{array}{c} (k,l,e,y,s,d,w) : \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} k_{nt} \le k, \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} l_{nt} \le l \\ \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda_{it} e_{it} \le e, \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda_{it} y \ge y, \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda_{it} s_{it} = s \\ \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda_{it} d_{it} = d, \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda_{it} w = w, \lambda_{it} \ge 0 \end{array} \right\} \tag{2}$$

Since the direction distance function changes the input and output in the same proportion [53,54], when there is relaxation, the efficiency value may be overestimated. To overcome the shortcomings of the radial measure of the directional distance function, the NDDF function with an unexpected output should be constructed [55], as shown in Equation (3):

$$\vec{ND} = (k,l,e,y,s,d,w;g) = sup\left\{ w^T \beta : ((k,l,e,y,s,d,w) + g \cdot diag(\beta)) \in P \right\} \tag{3}$$

In Equation (3), $w^T = (w_k, w_L, w_E, w_Y, w_S, w_D, w_W)$ is the weight vector of the input, expected output, and unexpected output variables; $g = (-g_k, -g_L, -g_E, g_Y, -g_S, -g_D, -g_w)$ stands for the direction vector; $\beta = (\beta_k, \beta_L, \beta_E, \beta_Y, \beta_S, \beta_D, \beta_w,)^T \ge 0$ represents the slack variable, which represents the expansion and reduction ratio of each input and output; $diag(\beta)$ is a diagonalized vector.

Since the nonparametric DEA model lacks a specific functional form, there is no clear division basis for the weights of various input variables and output variables, and equalization is a more reasonable method of assignment [56]. To eliminate the impact of capital and labor changes on energy efficiency, the energy input, expected output, and unexpected output can be given by the same weight, and the weight vector is set as $w^T = \left(0, 0, \frac{1}{3}, \frac{1}{3}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9},\right)$, the corresponding direction vector is $g = (0, 0, -e, y, -s, -d, -w)$, and the corresponding linear programming is:

$$\begin{array}{c} \vec{ND} = (k,l,e,y,s,d,w) = \\ max\left\{ \frac{1}{3}\beta_e + \frac{1}{3}\beta_y + \frac{1}{9}\beta_s + \frac{1}{9}\beta_d + \frac{1}{9}\beta_w \right\} \end{array} \tag{4}$$

Energy efficiency ($ee$) can be expressed as:

$$ee_{it} = \frac{1}{6}\left[ \begin{array}{c} \frac{y_{it}/e_{it}}{\left(y_{it}+\beta^*_{y,it}y_{it}\right)/e_{it}-\beta^*_{e,it}e_{it}} + \frac{y_{it}/s_{it}}{\left(y_{it}+\beta^*_{y,it}y_{it}\right)/s_{it}-\beta^*_{s,it}s_{it}} \\ + \frac{y_{it}/d_{it}}{\left(y_{it}+\beta^*_{y,it}y_{it}\right)/d_{it}-\beta^*_{d,it}d_{it}} + \frac{y_{it}/w_{it}}{\left(y_{it}+\beta^*_{y,it}y_{it}\right)/w_{it}-\beta^*_{w,it}w_{it}} \end{array} \right] \tag{5}$$

### *4.2. Model Construction*

To examine the impact of digital finance on energy efficiency, this study constructed a fixed effects model: the benchmark model represented by Equation (6):

$$ee_{it} = \alpha_0 + \alpha_1 df_{it} + \sum_i^4 \alpha_i Z_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{6}$$

In Equation (6), $i$ stands for one city and $t$ denotes a year, $ee_{it}$ is a dependent variable and represents energy efficiency; $df_{it}$ is an explanatory variable and represents digital finance, and $cb_{it}, ud_{it}, dl_{it}$ are sub-indicators of digital finance, representing the coverage breadth, usage depth, and digitization level, respectively. $Z_{it}$ denotes control variables, including economic development $(pgdp)$, local government fiscal expenditure $(gov)$, industrial structure $(is)$, openness $(open)$, and environmental regulation $(er)$. $\mu_i$ indicates the city fixed effect; $\gamma_t$ indicates the time fixed effect; $\varepsilon_{it}$ represents the random error term.

To clarify the ways in which digital finance affects energy efficiency, a moderation effect model was constructed based on Equation (6):

$$ee_{it} = \alpha_0 + \alpha_1 df_{it} + \alpha_2 gp_{it} + \alpha_3 df_{it} \times gp_{it} + \sum_i^4 \alpha_i Z_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (7)$$

$$ee_{it} = \alpha_0 + \alpha_1 df_{it} + \alpha_2 ti_{it} + \alpha_3 df_{it} \times ti_{it} + \sum_i^4 \alpha_i Z_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (8)$$

In Equations (7) and (8), $gp_{it}$ represents green technology innovation and $ti_{it}$ is R&D investment. $df_{it} \times gp_{it}$ indicates the interaction between digital finance and green technology innovation. $df_{it} \times ti_{it}$ indicates the interaction between digital finance and R&D investment. If the coefficient for the interaction term is statistically significant, it means that the interaction term can have an appreciable impact on energy efficiency; It implies that digital finance does have a significant impact on energy efficiency, either positively or negatively, and that it must be combined with technological advancement to be effective. If the coefficient of $gp_{it}$ or $ti_{it}$ is not significant, but the interactive term is significant, this indicates that the interactive term needs the support of digital finance to play a significant role. If the coefficient of $gp_{it}$ or $ti_{it}$ is not significant, but the interactive term is significant, it indicates that the interactive term needs the support of digital finance to play a significant role.

To further test the spatial effect on the basis of Equation (6), we introduced a spatial weight matrix, with the model taking the specific form shown in Equation (9):

$$\begin{gathered} ee_{it} = \alpha + \rho \sum_{i=1}^n wee_{it} + + \alpha_1 df_{it} + \varphi \sum_{i=1}^n wdf_{it} + \eta \sum_{i=1}^n Z_{it} \\ + \mu_i + (\lambda w \varepsilon_{it} + \nu_{it}) \end{gathered} \quad (9)$$

The variables $ee_{it}$, $df_{it}$ and $Z_{it}$ are the same as in Equation (6). $\rho$ represents the spatial correlation coefficient, which is used to capture the spatial spillover effect of digital finance and energy efficiency, where $w$ represents the spatial relationship between regions. $\lambda$ is a spatial error term and $v_{it}$ is a random error term. When $\lambda = 0$, the spatial lag model (SLM) condition can be satisfied. When $\rho = 0$, the spatial error model (SEM) condition can be satisfied, and the LM test was used to select the model.

### *4.3. Variable Description and Data Source*

#### 4.3.1. Explained Variable: Energy Efficiency

The total factor energy efficiency index of 278 cities was measured by the NDDF in this study. Capital stock, labor, and energy consumption were selected as the inputs, the gross regional product (gdp) was selected as an expected output, and industrial sulfur dioxide (s), industrial smoke and dust (d), and industrial wastewater (w) were selected as unexpected outputs [29,57]. Figure 2 depicts regional differences and dynamic changes in energy efficiency. China has a stable growth trend in energy efficiency, although its level is relatively low. The average energy efficiency in 2011 was 0.19 and rose to 0.36 in 2019. There were significant differences between regions in terms of spatial distribution. In 2019, the energy efficiency of the eastern region was higher than that of other regions at 0.42, followed by 0.36 in the northeast region, 0.35 in the central region, and 0.3 in the western region.

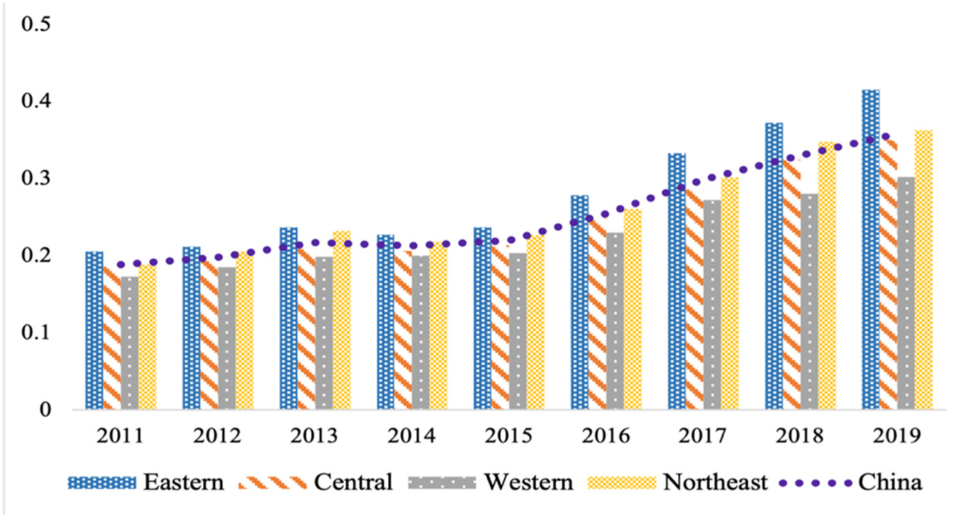


**Figure 2.** Energy efficiency from 2011 to 2019.

#### 4.3.2. Key Explanatory Variable: Digital Finance

This paper adopts the index of digital finance as the key explanatory variable, which was compiled by the Peking University Digital Finance Research Center based on the relevant data of ant financial, and used to measure the development level of digital inclusive finance in various regions of China [58]. This index covers three sub-dimensions, including coverage breadth, use depth, and digitization level. See Table A1 in Appendix A.

Figure 3 illustrates the regional differences and dynamic changes in digital finance. We compared digital finance in 2011 and 2019 and found that there has been a significant increase in digital finance, from 0.522 to 2.462, with an average growth rate of 21.39%. As for spatial differentiation, the eastern region was in the leading position, and the central and western regions had a rapid development momentum.

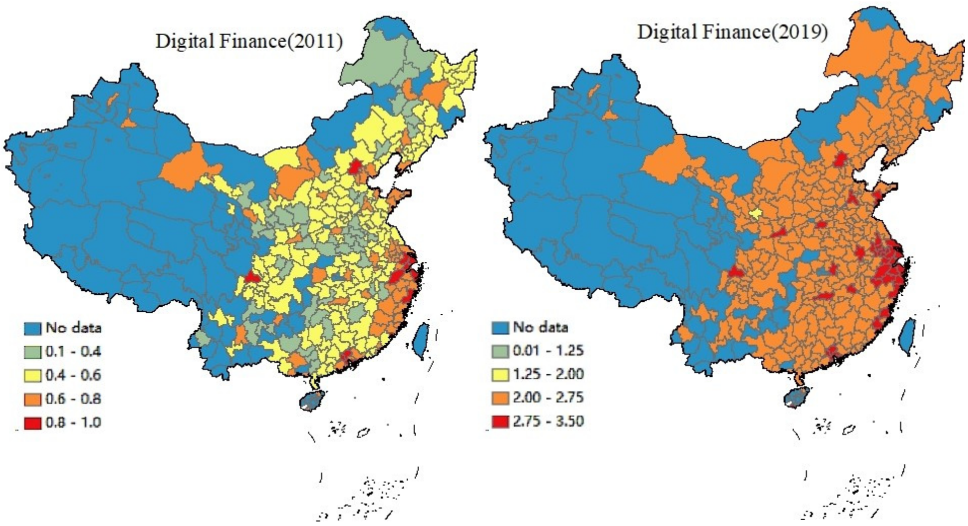


**Figure 3.** Digital finance development of 278 cities in 2011 and 2019.

#### 4.3.3. Moderating Variables

Research and development investment $(ti)$. R&D investment can improve production efficiency and promote sustainable growth, which can lead to energy conservation and emission reduction [59,60]. According to the previous research, this paper employs the proportion of scientific expenditure in fiscal expenditure to express R&D investment.

Green technology innovation $(gp)$. The effects of technological development on energy use and $CO_2$ emissions vary significantly. While improving production efficiency, production-oriented technological progress can induce problems such as "energy rebound", whereas green technological progress can help promote energy conservation and emissions reduction [11]. The number of green patents granted not only reflects the quantity of green technology innovation activity but also characterizes its quality. For this reason, we chose the number of green patents to be granted as a proxy variable for innovation in green technologies.

#### 4.3.4. Control Variables

To lessen the impact of other factors, we introduced a set of control variables. Economic development $(pgdp)$, this paper adopted GDP per capita to reflect the level of regional economic development [40]. Government intervention $(gov)$: we employed the ratio of local government fiscal expenditure to regional GDP as a proxy variable [61]. The industrial structure $(is)$ was measured as the proportion of secondary industry in GDP [45]. This paper chose the ratio of total exports and imports to GDP to measure their degree of openness to the outside world (open) [62]. Environmental regulation (*er*) was represented by the revised environmental regulation intensity index [43].

#### 4.3.5. Data Sources

This paper used the panel data of 278 cities in China from 2011 to 2019. The relevant data are from the China City Statistical Yearbook (2012–2020) and the Provincial Statistical Yearbook (2012–2020). Digital finance comes from the Peking University Digital Inclusive Financial Index [58]. To eliminate the impact of price factors, all variables, including price factors, were deflated based on 2011. Table A2 in Appendix B shows the variable description and descriptive statistics.

## 5. Empirical Results

### *5.1. Benchmark Regression Analysis*

In the benchmark model, we mainly tested the impact of digital finance on energy efficiency (as shown in Table 1). In order to ensure the robustness of the regression results, we progressively added control variables to the regression analysis. The results demonstrated that digital finance enhanced energy efficiency at a 1% significance level, and after gradually adding the control variables, the results remained positive. Digital finance can improve energy efficiency, which verifies hypothesis 1. This observation is in line with previous research conclusions [50,63]. This may be connected with the rise of digital finance and its beneficial consequences. From a production point of view, the automation of production processes through information and communication technology (ICT) and operation-oriented ICT investments or equipment has reduced energy consumption. From a consumer aspect, digital finance fosters a green way of consumption, making online payments convenient, reducing the travel demands generated by economic transactions and reducing energy consumption. Regression results for the control variables show that economic development $(pgdp)$, government intervention $(gov)$, and environmental regulation (*er*) can also contribute to improvements in energy efficiency. The greater the $pgdp$, the more conducive it is to provide financial support for R&D activities, to improve production technology and energy efficiency. Government intervention $(gov)$ and environmental regulation (*er*) can also contribute to energy efficiency to some extent. Nevertheless, the industrial structure $(is)$ is positive for energy efficiency but not significantly, indicating that energy conservation and sustainable development can be ignored in some areas. The *open* is negative as it inhibits energy efficiency. As industries with high energy consumption and high pollution levels are being relocated to China, this is leading to an increase in domestic energy consumption.

**Table 1.** The results of benchmark regression.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| **Variables** | **ee** | **ee** | **ee** | **ee** | **ee** | **ee** |
| df | 0.1712 *** | 0.1195 *** | 0.1362 *** | 0.1351 *** | 0.1282 *** | 0.1286 *** |
| | (5.046) | (3.439) | (3.828) | (3.771) | (3.570) | (3.707) |
| pgdp | | 0.0181 *** | 0.0190 *** | 0.0190*** | 0.0178*** | 0.0199 *** |
| | | (5.983) | (6.225) | (6.216) | (5.736) | (6.638) |
| gov | | | 0.1334 ** | 0.1392 ** | 0.1345 ** | 0.1783 *** |
| | | | (2.152) | (2.121) | (2.051) | (2.812) |
| is | | | | 0.0144 | 0.0078 | 0.0140 |
| | | | | (0.267) | (0.144) | (0.269) |
| open | | | | | −0.0462 ** | −0.0273 |
| | | | | | (−2.320) | (−1.415) |
| er | | | | | | 0.0226 *** |
| | | | | | | (12.709) |
| Constant | 0.0992 *** | 0.0552 *** | 0.0207 | 0.0124 | 0.0349 | −0.0213 |
| | (5.384) | (2.800) | (0.816) | (0.311) | (0.849) | (−0.533) |
| City | Yes | Yes | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 2502 | 2502 | 2502 | 2502 | 2502 | 2502 |
| R-squared | 0.356 | 0.366 | 0.368 | 0.368 | 0.369 | 0.412 |
| Number of cities | 278 | 278 | 278 | 278 | 278 | 278 |

Note: ***, ** means statistical significance at the 1% and 5%, t-values are shown in brackets.

### *5.2. Endogeneity and Robustness Test*

Endogenous test. First, it was possible that there would be a two-way causal relationship between digital finance and energy efficiency. On one hand, digital finance can improve the supply of capital and help expand capacity by easing financing constraints, causing businesses to consume energy and grow rapidly. On the other hand, under the constraints of reducing emissions and conserving energy, enterprises need to adopt clean technology in production, and the funding gap for technology research and development is the penetration of digital finance in enterprises. Secondly, as the economy and society develop, the variables influencing energy efficiency change, and thus, the endogenous problem of missing variables in the regression model arises. As a result, this work attempted to use the instrumental variable (IV) method to address this endogenous issue. We applied 2SLS to the endogeneity test, where the product of the first-order lag of digital finance and the first-order time difference of digital finance was used as the IV [64,65]. The results are shown in Table 2. In the first stage, the estimated coefficient values of IVs were significant at the 1% level with an F-value greater than the critical value of 16.38 [66], indicating that the test for weak instrumental variables could be passed and the selected IVs were reasonably valid. The results of the regression, were consistent with the results of benchmark regression. Improving energy efficiency can be supported by the development of digital finance, verifying that the research conclusions of this paper are effective and robust.

**Table 2.** Endogeneity test results.

| | (1) | (2) |
|---|---|---|
| **Variables** | **First–Stage df** | **Second–Stage ee** |
| L.df × D.df | 0.3817 *** | |
| | (34.86) | |
| df | | 0.2218 *** |
| | | (3.57) |
| pgdp | 0.0158 *** | 0.0234 *** |
| | (9.75) | (6.50) |

**Table 2.** *Cont.*

| | (1) | (2) |
|---|---|---|
| **Variables** | **First–Stage**<br>**df** | **Second–Stage**<br>**ee** |
| gs | −0.2127 *** | 0.2051 *** |
| | (−6.93) | (2.99) |
| is | 0.1368 *** | −0.0269 |
| | (5.19) | (−0.46) |
| open | −0.0328 *** | −0.0193 |
| | (−3.20) | (−0.87) |
| er | −0.0008 | 0.0243 *** |
| | (−0.85) | (12.39) |
| City | Yes | Yes |
| Year | Yes | Yes |
| Observations | 2224 | 2224 |
| R–squared | | 0.404 |
| Number of cities | 278 | 278 |

Note: *** means statistical significance at the 1%, t-values are shown in brackets.

Table 3 shows the robustness results of this study.

**Table 3.** Robustness test.

| | (1) | (2) | (3) |
|---|---|---|---|
| **Variables** | **ee** | **ee** | **ee** |
| L.eg | | | 0.6213 *** |
| | | | (29.458) |
| df | 0.1168 *** | 0.1405 *** | 0.0210 *** |
| | (3.3542) | (3.7852) | (5.919) |
| pgdp | 0.0184 *** | 0.0214*** | 0.0081 *** |
| | (6.1103) | (6.7109) | (5.015) |
| gov | 0.1647 *** | 0.1751*** | 0.1337 *** |
| | (2.5950) | (2.7139) | (3.451) |
| is | 0.0117 | 0.0068 | −0.0266 |
| | (0.2254) | (0.1246) | (−0.750) |
| open | −0.0090 | −0.0171 | −0.0201 *** |
| | (−0.4603) | (−0.8441) | (−2.684) |
| er | 0.0216 *** | 0.0219*** | 0.0241 *** |
| | (12.0703) | (12.1502) | (15.704) |
| Constant | −0.0062 | −0.0266 | −0.0184 |
| | (−0.1568) | (−0.6361) | (−0.760) |
| City | Yes | Yes | Yes |
| Year | Yes | Yes | Yes |
| Observations | 2466 | 2429 | 2224 |
| R–squared | 0.3989 | 0.3967 | |
| Number of cities | 274 | 278 | 278 |

Note: *** means statistical significance at the 1%, t-values are shown in brackets.

1. Delete the municipalities. China's municipalities are directly managed by the central government. These cities have more built-up areas and permanent residents and play a significant part in domestic politics and the economy. Four municipalities were deleted to avoid the bias caused by municipalities. The coefficient of digital finance was 0.1168 at a significance level of 1% (column 1). Digital financing does provide support for improving energy efficiency.

2. Delete extreme values. We carried out a 1% tailing treatment on the explained variable and the key explanatory variable. The estimated coefficient of 0.1405 for digital finance at the 1% significance level (column 2) indicated that the positive impact of digital

finance on energy efficiency remained significant, which is consistent with the results of benchmark regression.

3. Change the analysis method. Given that technological and production efficiency improvements can take time, energy efficiency improvements can be delayed. Therefore, the regression model used a system-generalized method of moments (SYS-GMM) and included the explanatory variable's first-order lag term. The model has passed the Arellano Bond test and the Sargan test, and the findings demonstrate that digital finance can enhance energy efficiency so that the estimation results of SYS-GMM are consistent and reliable.

The above results show that the benchmark regression is credible.

### *5.3. Heterogeneity Analysis*

In order to explore in more detail the heterogeneity of the impact of digital financing on energy efficiency, this paper presented a differentiated analysis in the following different contexts.

1. The sub-indicator of digital finance. Digital finance is composed of the coverage breadth (cb), usage depth (ud) and digitization level (dl), which can reflect the development of digital finance from three aspects. Table 4 shows that the usage depth and digitization level can have an impact on energy efficiency. The estimated coefficient values for *ud* and *dl* were 0.0449 and 0.0348, respectively, and were statistically significant at the 5% and 1% levels. However, coverage breadth hinders energy but fails to pass the significance test. The reason for this could be that the coverage of digital finance is limited, and the SMEs have difficulties in acquiring funds, which results in insufficient R&D investment and poor production technology. Therefore, energy consumption cannot be reduced; hence, it is impossible to increase energy efficiency.

**Table 4.** Heterogeneity test on digital finance dimensions and development level.

| | **Dimensional Heterogeneity** | | | **DF Heterogeneity** | |
|---|---|---|---|---|---|
| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** |
| cb | −0.0086 | | | | |
| | (−0.2428) | | | | |
| ud | | 0.0449 ** | | | |
| | | (2.0254) | | | |
| dl | | | 0.0348 *** | | |
| | | | (4.2205) | | |
| df | | | | 0.1040 ** | 0.1566 *** |
| | | | | (2.3138) | (2.7052) |
| Controls | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.0374 | 0.0125 | 0.0221 | −0.0867 * | 0.0163 |
| | (0.9283) | (0.3223) | (0.5936) | (−1.8400) | (0.1872) |
| City | Yes | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes | Yes |
| Observations | 2502 | 2502 | 2502 | 1485 | 1017 |
| R–squared | 0.4085 | 0.4095 | 0.4131 | 0.4489 | 0.4159 |
| Number of cities | 278 | 278 | 278 | 165 | 113 |

Note: ***, **, * means statistical significance at the 1%, 5% and 10%, t-values are shown in brackets.

2. The different development levels of digital finance. Taking the average value of digital finance development as the standard, it can be divided into the backward areas of digital finance (column 4), and the developed areas of digital finance (column 5) to explore the impact of the difference in the development levels of digital finance on energy efficiency. The results show that digital finance has enhanced energy efficiency. In particular, the contribution of this is more pronounced in areas with advanced digital finance. The more developed regional digital finance is, the easier it is to overcome the problem of resource mismatch, which is conducive to improving the production efficiency of enterprises. Meanwhile, companies can access low-cost capital through a variety of

channels, which promotes the adoption of green technologies in production and drives innovation in green technologies. Therefore, the impact of digital financing on improving energy efficiency is more pronounced in more developed areas of digital finance.

3. Different regions. Natural resources, location, economic growth, and policies all have varying effects on regional development. This paper divides the country into the eastern region, the central region, the western region, and the northeast region and discusses regional differences in the impact of digital finance on energy efficiency. Table 5 shows that digital finance improves energy efficiency in the central, western, and northeastern regions (columns 1 to 4). With a better digital financial infrastructure, digital finance can highlight its complementary role in traditional finance. Therefore, in the central region, digital finance contributes more to increased energy efficiency. The western region has abundant energy resources, but economic development is lagging, and technological advancement is inadequate, resulting in low energy efficiency. Digital finance can provide convenient financial support for innovation and entrepreneurship activities, guide advanced green technologies, and help improve energy efficiency because of its inclusive feature. The northeast region demonstrated a low level of economic development, insufficient investment in digital finance infrastructure, and relatively backward high-tech industry construction, making it difficult to support digital finance development. This makes it difficult for digital finance to drive energy efficiency [67,68]. Digital finance tends to limit energy efficiency in the eastern region. In the eastern region, the financial service system is relatively perfect. The industry and financial system have established a stable relationship between banks and enterprises, which has a crowding-out effect on digital finance. It is, therefore, detrimental to the optimization of industrial structures or the promotion of green technology. Meanwhile, there has been an increase in energy consumption as a result of the widespread use of digital infrastructure and Internet technologies [69]. Therefore, digital finance in the eastern region has inhibited energy efficiency.

**Table 5.** Heterogeneity test on regions and resource.

| | **Regional Heterogeneity** | | | | **Resource Heterogeneity** | |
|---|---|---|---|---|---|---|
| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** |
| df | −0.0501 | 0.1875 *** | 0.1379 ** | 0.1269 | 0.1343 ** | 0.0826 * |
| | (−0.6040) | (3.7903) | (2.2092) | (0.8596) | (2.4324) | (1.7378) |
| Controls | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.0625 | −0.2050 *** | 0.1783 *** | −0.2916 ** | 0.0581 | −0.0298 |
| | (0.5354) | (−3.1443) | (2.7187) | (−2.2176) | (0.9213) | (−0.5595) |
| City | Yes | Yes | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 810 | 702 | 693 | 297 | 1008 | 1494 |
| R–squared | 0.4759 | 0.6609 | 0.2870 | 0.4124 | 0.2928 | 0.4936 |
| Number of cities | 90 | 78 | 77 | 33 | 112 | 166 |

Note: ***, **, * means statistical significance at the 1%, 5% and 10% significance levels, t-values are shown in brackets.

4. An analysis of the variability of resource endowments. The proportion of resource-based industries is higher in areas with abundant energy and resources, putting pressure on energy conservation and consumption reduction for enterprise development. We further divided the study sample into resource-based and non-resource-based cities. The outcomes of this demonstrated that the coefficient of digital finance was estimated to be 0.1343 at a 5% significance level (column 5 of Table 5), indicating that the growth of digital finance in resource-based cities plays a typical role in improving energy efficiency. Resource-based regions are more dependent on energy, with more serious financial resource mismatch, large energy consumption and low energy efficiency. Digital finance can overcome the problems of “ownership discrimination” and “scale discrimination” in traditional finance, ease

financing constraints for SMEs, support industrial structure optimization and upgrading, and support low energy transformations in resource-based regions [70].

### *5.4. Mechanism Test*

The above research confirms that digital finance has a significant role in improving energy efficiency, but the mechanism for this has not yet been clarified. We investigated a mechanism via the moderation effect model. See Table 6.

**Table 6.** Mechanism test of green technology innovation and R&D investment.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| **Variables** | **ee** | **ee** | **ee** | **ee** |
| df | 0.0770 ** | 0.0789 ** | 0.1242 *** | 0.1107 *** |
| | (2.1977) | (2.2522) | (3.5615) | (3.1028) |
| gp | 0.3206 *** | 0.0595 | | |
| | (7.1607) | (0.4561) | | |
| df*gp | | 0.1378 ** | | |
| | | (2.1288) | | |
| ti | | | 0.2482 | 0.1734 |
| | | | (1.2119) | (0.8297) |
| df*ti | | | | 0.3236 * |
| | | | | (1.7727) |
| Controls | Yes | Yes | Yes | Yes |
| Constant | 0.0475 | 0.0476 | −0.0203 | −0.0030 |
| | (1.1681) | (1.1711) | (−0.5066) | (−0.0733) |
| City | Yes | Yes | Yes | Yes |
| Year | Yes | Yes | Yes | Yes |
| Observations | 2502 | 2502 | 2502 | 2502 |
| R–squared | 0.4254 | 0.4266 | 0.4125 | 0.4133 |
| Number of cities | 278 | 278 | 278 | 278 |

Note: ***, **, * means statistical significance at the 1%, 5% and 10% significance levels, t-values are shown in brackets.

The estimation findings in Table 6, columns (1) and (2) demonstrate that innovation in green technologies can boost energy efficiency. The coefficient of $df * gp$ was 0.1378 at a 5% significance level. Green technology innovation raises energy efficiency that is pursuant to digital finance. Digital finance can be integrated with green finance, and its related technology can spill over into green financial institutions, broadening = user scenarios and expanding the radiation of green financial services, guiding the flow of funds to green industries and environmentally friendly enterprises. Having benefited from convenient financing, enterprises can further intensify the R&D of green technologies, adopt green products and processes, and accelerate the innovation of green technologies.

R&D investment does have a positive effect on energy efficiency in columns (3) and (4) of the results, but this was insignificant. The coefficient of $df * ti$ was 0.3236 at a 10% significance level. Digital finance helps enterprises to capitalize on their own competitive advantages, grasp the development of the industry, stimulate the enthusiasm and initiative of R&D investment, and improve the production technology and the production efficiency of enterprises. On the other hand, digital finance improves the transparency of enterprises' production and operating processes, reduces the risk premium caused by information asymmetry, eases financing burdens on enterprises and allows them to invest more resources in technological innovation to improve their core competitiveness and production efficiency, thus reducing energy consumption. From this point of view, digital finance integrated with R&D investment and green technology innovation may play a role in improving energy efficiency.

## 6. Further Study

Regional economic activities cannot operate independently, and there are interactions between regions. To avoid the result deviation caused by spatial correlation, this paper incorporated spatial variables into the basic model (6).

We investigated how energy efficiency varied with space using the spatial inverse distance matrix, which is made by MATLAB. Moran's I and Gear's C (see Table A3 in Appendix C) showed a significant spatial autocorrelation in energy efficiency. Considering the test results of the Hausman test, Lagrange multiplier (LM), robust LM, Wald test, and likelihood ratio (LR) tests (see Table A3 in Appendix C), the spatial Durbin model (SDM) with double fixed effects was appropriate for this research. The spatial regression results are shown in Table 7. Energy efficiency was significantly aided by digital finance. When digital finance increased by 1 unit, the energy efficiency increased by 0.1243. Energy efficiency was also negatively affected by the growth of digital finance in neighboring regions. However, the effect of this was not significant.

**Table 7.** Effect of digital finance on energy efficiency: spatial regression findings.

| | **(1)** | **(1)** | **(2)** |
|---|---|---|---|
| **Variables** | **SDM** | **SLM** | **SAR** |
| df | 0.1243 *** | 0.1282 *** | 0.1273 *** |
| | (3.8404) | (3.9463) | (3.9277) |
| W × df | −0.1557 | | |
| | (−0.3070) | | |
| Controls | Yes | Yes | Yes |
| City | Yes | Yes | Yes |
| Year | Yes | Yes | Yes |
| $\lambda$ | | −0.9800 *** | |
| | | (−3.9980) | |
| $\rho$ | −1.3492 *** | | −0.8784 *** |
| | (−5.1120) | | (−3.7691) |
| Observations | 2502 | 2502 | 2502 |
| R–squared | 0.2764 | 0.3182 | 0.3237 |
| Number of cities | 278 | 278 | 278 |

Note: *** means statistical significance at the 1%, t-values are shown in brackets.

Using spatial effects decomposition, the impact of digital finance on energy efficiency can be broken down into direct, indirect and total effects. (See Table 8).

**Table 8.** Spatial effect decomposition of double fixed effect SDM.

| | **(1)** | **(2)** | **(3)** |
|---|---|---|---|
| **Variables** | **Direct Effect** | **Indirect Effect** | **Total Effect** |
| df | 0.1275 *** | −0.1391 | −0.0116 |
| | (3.8514) | (−0.6050) | (−0.0498) |
| Controls | Yes | Yes | Yes |
| City | Yes | Yes | Yes |
| Year | Yes | Yes | Yes |
| Observations | 2502 | 2502 | 2502 |
| R–squared | 0.2764 | 0.2764 | 0.2764 |
| Number of id | 278 | 278 | 278 |

Note: *** means statistical significance at the 1%, t-values are shown in brackets.

Energy efficiency has been considerably enhanced by digital finance. The coefficient of $df$ is estimated to be 0.1275 at the 1% significance level (column 1), indicating that at a 1 unit increase in digital finance, local energy efficiency would increase by 0.1275. Despite being estimated to be −0.1391, the coefficient of indirect effect failed the significance test. This indicates that the development of local digital finance may tend to inhibit the energy efficiency of neighboring areas, and the following are some potential causes: local digital finance would boost a city's economic development, and further improvements in digital infrastructure could create more jobs. It is easier for the locals to retain technology enterprises and high-end talents. Meanwhile, due to the potential loss of technology, talent, and capital in neighboring areas, it would not be conducive to technological progress, and the production mode of high energy consumption would remain. Furthermore, the direct effect of digital finance is positive and significant compared to the indirect effect, suggesting that the positive impact of digital finance on energy efficiency would only be effective when applied to production in the region. Combined with the heterogeneity analysis, the coverage of digital finance is limited, the financing channels of SMEs have not been fully opened, and there are financing constraints, resulting in insufficient R&D investment, production technology that is difficult to update, and difficulties in reducing energy consumption under a high energy consumption mode. Therefore, in the short term, the growth of digital finance tends to be energy efficient.

## 7. Conclusions and Policy Implications

In this paper, the implications of digital finance on urban energy efficiency can be examined quantitatively. The NDDF was employed in the calculation of energy efficiency, after which we examined how energy efficiency and digital finance were related and discussed the mechanism and spatial effect. These findings prove that digital finance can notably promote energy efficiency. Moreover, the usage depth and digitization level can improve energy efficiency while coverage inhibits it; developed digital finance regions, central regions, and resource-based cities have all seen energy efficiency improvements. Furthermore, green technology innovation and R&D investment are mechanisms for digital finance to promote energy efficiency. Finally, further research has revealed that digital finance is capable of improving local energy efficiency while inhibiting neighboring areas' efficiency. The proposals of the preceding results are as follows:

First, policymakers ought to focus on how digital finance could potentially advance energy efficiency. The government should take advantage of the strategic opportunities presented by a new wave of scientific and technological revolution, bolster the creation of infrastructure for digital technologies, and support the growth of advanced technologies, such as big data and blockchain, expanding the availability of digital financial services and digitization rates. To promote energy conservation, reduce emissions, and further unleash the energy-saving effect of digital finance, the government should strengthen the guidance of policies related to it.

Second, to benefit SMEs, the administration should encourage the use of digital finance in production and day-to-day activities, improve production technology, and increase energy efficiency. To provide economic support for SMEs' technological innovation, low-development zones for digital finance should improve digital infrastructure construction and digital service capacity. To achieve the coordinated development of digital finance, the western region and northeastern region should use policy support to accelerate digital finance's advancement, improve digital and financial infrastructure construction, and lay a solid foundation. In terms of resource endowment differences, resource-based cities should prioritize improving digital finance, guiding the rational allocation of financial, digital, and other elements, and playing a role in improving the mode of production to decrease the use of energy and increase the effectiveness of utilizing energy.

Third, green technology innovation and R&D investment should be viewed as two distinct ways for digital finance to promote energy efficiency. On the one hand, to foster green technology innovation, the digital financial system should be improved. Innovating green technologies should be promoted by enterprises, and the application of green technology innovation should be broadened in the production field to promote energy efficiency. On the other hand, the integrated development of digital finance and R&D investment should be emphasized.

Finally, given the potential spatial spillover effect between cities, the interplay between urban agglomerations should be considered by the government when developing policies. To accelerate the transfer of knowledge and technology from high-energy-efficiency areas to low-energy-efficiency areas, it is critical to remove digital barriers and the challenges associated with information blockage in order to fully utilize the benefits that digital finance can provide in integrating resources across geographies and prioritize the exchange and sharing of information and technology between regions.

**Author Contributions:** Conceptualization, Y.W., Y.L., and M.Z.; Methodology, Y.L. and M.Z.; Formal analysis, Y.L.; Writing - original draft, Y.L.; Writing - review & editing, Y.W. and M.Z.; Investigation, Y.L.; Software, Y.L.; Data curation, Y.L. and M.Z.; Visualization, Y.W. and M.Z.; Supervision, Y.L.; Funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Natural Science Foundation of China (Funding No. 71703060) and Humanities and Social Sciences Youth Foundation, Ministry of Education of the People's Republic of China (17YJC790170).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** System for digital finance indicators.

| Primary Indicators | Secondary Indicators | Specific Explanation of Indicators |
| --- | --- | --- |
| Coverage breadth | Account coverage | Number of Alipay accounts per 10,000 people |
| | | Proportion of Alipay bundled card users |
| | | Average number of bank cards bound to each Alipay account |
| Usage depth | Payment business | Number of payments per capita |
| | | Amount paid per capita |
| | | The proportion of active users with high frequency (50 or more active times per year) to active users with one or more active times per year |
| | Monetary fund business | Number of per capita purchases of yu'e bao |
| | | Amount of yu'e bao purchased per capita |
| | | Number of people per 10,000 Alipay users purchasing yu'e bao |
| | Credit business (for individual users) | Number of users with internet consumer loans per 10,000 adult Alipay users |
| | | Number of loans per capita |
| | | Loan amount per capita |
| | Credit business (for small and micro business operators) | Number of users with internet micro business loans per 10,000 adult Alipay users |
| | | Average number of loans per household of small and micro business operators |
| | | Average loan amount of small and micro business operators |

**Table A1.** *Cont.*

| Primary Indicators | Secondary Indicators | Specific Explanation of Indicators |
|---|---|---|
| | Insurance business | Number of insured users per 10,000 Alipay users |
| | | Number of insurance strokes per capita |
| | | Amount of insurance per capita |
| | Investment business | Number of Alipay users participating in Internet investment and financial management per 10,000 people |
| | | Number of investment per capita |
| | | Investment amount per capita |
| | Credit business | Number of people using credit-based life services per 10,000 Alipay users |
| | | Number of calls per natural person |
| Digitization level | Mobility | Proportion of mobile payments |
| | | Proportion of mobile payment amount |
| | Affordability | Average loan interest rate of small and micro business operators |
| | | Average individual loan interest rate |
| | Crediting | Proportion of the number of Huabei payments |
| | | Proportion of payment amount of Huabei |
| | | Proportion of sesame credit deposits exempted (more than all deposits required) |
| | | Proportion of sesame credit free deposit |
| | Facilitation | Proportion of QR code payment |
| | | Proportion of the amount of QR code payment |

## Appendix B

**Table A2.** Variable description.

| | Variable | Variable Description | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|---|
| Total factor productivity input variable | $k$ | capital stock | 2502 | 7110.47 | 8018.07 | 298.205 | 75,794.454 |
| | $l$ | labour | 2502 | 126.002 | 175.529 | 8.508 | 1729.08 |
| | $e$ | electricity consumption | 2502 | 190.272 | 213.744 | 0.002 | 1568.578 |
| | $y$ | gdp | 2502 | 2556.29 | 3336.34 | 133.745 | 32,885.433 |
| | $d$ | industrial fumes | 2502 | 345.998 | 1492.07 | 0.39 | 51,688.12 |
| | $w$ | industrial wastewater | 2502 | 60.949 | 78.206 | 0.07 | 1107.63 |
| | $s$ | sulfur dioxide emissions | 2502 | 504.878 | 905.44 | 0.02 | 15,000 |

**Table A2.** *Cont.*

| | Variable | Variable Description | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|---|
| Regression variables | *ee* | energy efficiency | 2502 | 0.253 | 0.151 | 0.039 | 1 |
| | *df* | digital finance | 2502 | 1.66 | 0.654 | 0.17 | 3.216 |
| | *gp* | green technology innovation | 2502 | 0.04 | 0.11 | 0 | 1.577 |
| | *ti* | research and development investment | 2502 | 0.017 | 0.017 | 0.001 | 0.207 |
| | *cb* | coverage breadth | 2502 | 1.566 | 0.633 | 0.019 | 3.109 |
| | *ud* | usage depth | 2502 | 1.638 | 0.68 | 0.043 | 3.32 |
| | *dl* | digitization | 2502 | 2.014 | 0.821 | 0.027 | 5.812 |
| | *pgdp* | economic development | 2502 | 5.416 | 3.468 | 0.692 | 27.7 |
| | *gov* | government intervention | 2502 | 0.196 | 0.097 | 0.044 | 0.916 |
| | *open* | opening to the outside world | 2502 | 0.18 | 0.291 | 0 | 2.491 |
| | *is* | industrial structure | 2502 | 0.471 | 0.106 | 0.117 | 0.893 |
| | *er* | environmental regulation | 2502 | 1.34 | 1.861 | 0.017 | 34.858 |

## Appendix C

**Table A3.** Results of Moran's I and Gear's C for energy efficiency.

| Year | Moran's I | Z–Value | Gear's C | Z–Value |
|---|---|---|---|---|
| 2011 | 0.008 ** | 2.385 | 0.908 *** | −2.779 |
| 2012 | 0.003 | 1.387 | 0.944 * | −1.903 |
| 2013 | 0.005 * | 1.784 | 0.927 *** | −2.716 |
| 2014 | 0.009 ** | 2.444 | 0.926 ** | −2.589 |
| 2015 | 0.019 *** | 4.447 | 0.970 | −1.172 |
| 2016 | 0.016 *** | 3.855 | 0.950 *** | −2.626 |
| 2017 | 0.016 *** | 3.784 | 0.962 ** | −2.311 |
| 2018 | 0.009 ** | 2.474 | 0.971 ** | −2.127 |
| 2019 | 0.011 *** | 2.816 | 0.966 ** | −2.539 |

Note: ***, **, * means statistical significance at the 1%, 5% and 10% significance levels, respectively.

## References

1. Liu, H.; Zhang, Z.; Zhang, T.; Wang, L. Revisiting China's provincial energy efficiency and its influencing factors. *Energy* **2020**, *208*, 118361. [CrossRef]
2. Zhou, S.; Xu, Z. Energy efficiency assessment of RCEP member states: A three-stage slack based measurement DEA with undesirable outputs. *Energy* **2022**, *253*, 124170. [CrossRef]
3. Wang, Z.; Wang, X. Research on the impact of green finance on energy efficiency in different regions of China based on the DEA-Tobit model. *Resour. Policy* **2022**, *77*, 102695. [CrossRef]
4. Yu, J.; Zhang, R.; Gong, X. How Does Digital Finance Affect Green Total Factor Productivity: Characteristics of Dynamics, Identification of Mechanisms and Spatial Effects. *Mod. Econ. Sci.* **2022**, *44*, 42–56.
5. Fan, X.; Yin, S. Does Digital Finance Promote Green Total Factor Productivity? *J. Shanxi Univ. Philosophy Soc. Sci.* **2021**, *44*, 58–66.

6. Qin, X.; Wu, H.; Li, R. Digital finance and household carbon emissions in China. *China Econ. Rev.* **2022**, *76*, 101872. [CrossRef]
7. Du, J.; Shiwei, W.; Wenyang, W. Does Digital Financial Inclusion Promote the Optimization of Industrial Structure? *Comp. Econ. Soc. Syst.* **2020**, *6*, 38–49.
8. Xue, Q.; Feng, S.; Chen, K.; Li, M. Impact of Digital Finance on Regional Carbon Emissions: An Empirical Study of Sustainable Development in China. *Sustainability* **2022**, *14*, 8340. [CrossRef]
9. Dong, J.; Dou, Y.; Jiang, Q.; Zhao, J. Can financial inclusion facilitate carbon neutrality in China? The role of energy efficiency. *Energy* **2022**, *251*, 123922. [CrossRef]
10. Wan, J.; Zhou, Q.; Xiao, Y. Digital Finance, Financial Constraint and Enterprise Innovation. *Econ. Rev.* **2020**, *1*, 71–83.
11. Wang, J.; Wang, J.; Wang, Y. How Does Digital Finance Affect the Carbon Intensity of the Manufacturing Industry? *China Popul. Environ.* **2022**, *32*, 1–11.
12. Patterson, M.G. What is energy efficiency? Concepts, Indicators and Methodological Issues. *Energy Policy* **1996**, *24*, 377–390. [CrossRef]
13. Liu, Y.; Wang, K. Energy efficiency of China′s industry sector: An adjusted network DEA (data envelopment analysis)-based decomposition analysis. *Energy* **2015**, *93*, 1328–1337. [CrossRef]
14. Wei, Z.; Han, B.; Pan, X.; Shahbaz, M.; Zafar, M.W. Effects of Diversified Openness Channels on the Total-Factor Energy Efficiency in China's Manufacturing Sub-Sectors: Evidence from Trade and FDI Spillovers. *Energy Econ.* **2020**, *90*, 104836. [CrossRef]
15. Aigner, D.; Lovell, C.A.K.; Schmidt, P. Formulation and estimation of stochastic frontier production function models. *J. Econom.* **1977**, *6*, 21–37. [CrossRef]
16. Kang, J.; Yu, C.; Xue, R.; Yang, D.; Shan, Y. Can regional integration narrow city-level energy efficiency gap in China? *Energy Policy* **2022**, *163*, 112820. [CrossRef]
17. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
18. Banker, R.D.; Charnes, A.; Cooper, W.W. Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Manag. Sci.* **1984**, *30*, 1078–1092. [CrossRef]
19. Tone, K. A slacks-based measure of super-efficiency in data envelopment analysis. *Eur. J. Oper. Res.* **2002**, *143*, 32–41. [CrossRef]
20. Ma, M.; Wang, Q. Assessment and Forecast of Green Total Factor Energy Efficiency in the Yellow River Basin—A Perspective Distinguishing the Upper, Middle and Lower Stream. *Sustainability* **2022**, *14*, 2506. [CrossRef]
21. Feng, Y.; Lu, C.-C.; Lin, I.-F.; Yang, A.-C.; Lin, P.-C. Total Factor Energy Efficiency of China's Thermal Power Industry. *Sustainability* **2022**, *14*, 504. [CrossRef]
22. Du, K.; Lu, H.; Yu, K. Sources of the Potential CO2 Emission Reduction in China: A Nonparametric Metafrontier Approach. *Appl. Energy* **2014**, *115*, 491–501. [CrossRef]
23. Xu, M.; Bao, C. Quantifying the spatiotemporal characteristics of China's energy efficiency and its driving factors: A Super-RSBM and Geodetector analysis. *J. Clean. Prod.* **2022**, *356*, 131867. [CrossRef]
24. Zhao, H.; Lin, B. Will Agglomeration Improve the Energy Efficiency in China's Textile Industry: Evidence and Policy Implications. *Appl. Energy* **2019**, *237*, 326–337. [CrossRef]
25. Yu, B. Industrial Structure, Technological Innovation, and Total-Factor Energy Efficiency in China. *Environ. Sci. Pollut. Res.* **2020**, *27*, 8371–8385. [CrossRef] [PubMed]
26. Shen, B.; Li, X. Financial Development, Industrial Structure Upgrading and Energy Efficiency Improvement. *Inq. into Econ. Issues* **2020**, 131–138.
27. Wu, H.; Hao, Y.; Ren, S.; Yang, X.; Xie, G. Does Internet Development Improve Green Total Factor Energy Efficiency? Evidence from China. *Energy Policy* **2021**, *153*, 112247. [CrossRef]
28. Zhao, S.; Hafeez, M.; Faisal, C.M.N. Does ICT Diffusion Lead to Energy Efficiency and Environmental Sustainability in Emerging Asian Economies? *Environ. Sci. Pollut. Res.* **2022**, *29*, 12198–12207. [CrossRef]
29. Shi, D.; Li, S. Emissions Trading System and Energy Use Efficiency—Measurements and Empirical Evidence for Cities at and above the Prefecture Level. *China Ind. Econ.* **2020**, 5–23. [CrossRef]
30. Li, B.; Han, Y.; Wang, C.; Sun, W. Did Civilized City Policy Improve Energy Efficiency of Resource-Based Cities?Prefecture-Level Evidence from China. *Energy Policy* **2022**, *167*. [CrossRef]
31. Yu, W.; Peng, Y.; Yao, X. The Effects of China's Supporting Policy for Resource-Exhausted Cities on Local Energy Efficiency: An Empirical Study Based on 284 Cities in China. *Energy Econ.* **2022**, 109181. [CrossRef]
32. Xie, X.; Shen, Y.; Zhang, H. Can Digital Finance Promote Entrepreneurship? —Evidence from China. *China Econ. Q.* **2018**, *17*, 1558–1580.
33. Li, J.; Wu, Y.; Xiao, J. The Impact of Digital Finance on Household Consumption: Evidence from China. *Econ. Model.* **2020**, 317–326. [CrossRef]
34. Lv, C.; Song, J.; Lee, C. Can Digital Finance Narrow the Regional Disparities in the Quality of Economic Growth? Evidence from China. *Econ. Anal. Policy* **2022**, *76*, 502–521. [CrossRef]
35. Sun, Y.; Tang, X. The Impact of Digital Inclusive Finance on Sustainable Economic Growth in China. *Financ. Res. Lett.* **2022**, *50*, 103234. [CrossRef]
36. Teng, L.; Ma, D. Can Digital Finance Help to Promote High-Quality Development. *Stat. Res.* **2020**, *37*, 80–92.

37. Chen, Y.; Yang, S.; Li, Q. How Does the Development of Digital Financial Inclusion Affect the Total Factor Productivity of Listed Companies? Evidence from China. *Financ. Res. Lett.* **2022**, *47*, 102956. [CrossRef]
38. Cheng, Y.; Dong, H.; Geng, J.; He, J. Energy Demand and Carbon Emission Peak Paths for the Rise of Central China. *Chinese J. Eng. Sci.* **2021**, *23*, 68. [CrossRef]
39. Wang, H.; Guo, J. Impacts of Digital Inclusive Finance on CO2 Emissions from a Spatial Perspective: Evidence from 272 Cities in China. *J. Clean. Prod.* **2022**, *355*, 131618. [CrossRef]
40. Feng, S.; Chong, Y.; Yu, H.; Ye, X.; Li, G. Digital Financial Development and Ecological Footprint: Evidence from Green-Biased Technology Innovation and Environmental Inclusion. *J. Clean. Prod.* **2022**, *380*, 135069. [CrossRef]
41. Fan, Q.; Feng, S. Mechanism and Effects of Digital Finance on Carbon Emissions. *China Popul. Environ.* **2022**, *32*, 70–82.
42. Xu, Z.; Gao, Y.; Huo, Z. Research on Pollution Reduction Effect of Digital Finance. *Financ. Econ.* **2021**, 28–39.
43. Zhang, M.; Liu, Y. Influence of Digital Finance and Green Technology Innovation on China's Carbon Emission Efficiency: Empirical Analysis Based on Spatial Metrology. *Sci. Total Environ.* **2022**, 156463. [CrossRef] [PubMed]
44. Paramati, S.R.; Mo, D.; Huang, R. The Role of Financial Deepening and Green Technology on Carbon Emissions: Evidence from Major OECD Economies. *Financ. Res. Lett.* **2021**, *41*. [CrossRef]
45. Wang, X.; Wang, X.; Ren, X.; Wen, F. Can Digital Financial Inclusion Affect CO2 Emissions of China at the Prefecture Level? Evidence from a Spatial Econometric Approach. *Energy Econ.* **2022**, 105966. [CrossRef]
46. Kim, K.; Bounfour, A.; Nonnis, A.; Ozaygen, A. Measuring ICT Externalities and Their Contribution to Productivity: A Bilateral Trade Based Approach. *Telecomm. Policy* **2021**, *45*. [CrossRef]
47. Lee, C.C.; Yuan, Z.; Wang, Q. How Does Information and Communication Technology Affect Energy Security? International Evidence. *Energy Econ.* **2022**, *109*, 105969. [CrossRef]
48. Duan, Y.; He, L.; Ke, H. Digital Finance, Technology Intensive Manufacturing and Green Development. *Shanghai J. Econ.* **2021**, *4*, 88–100. [CrossRef]
49. Liu, Y.; Xiong, R.; Lv, S.; Gao, D. The Impact of Digital Finance on Green Total Factor Energy Efficiency: Evidence at China' s City Level. *Energies* **2022**, *15*, 5455. [CrossRef]
50. Cao, S.; Nie, L.; Sun, H.; Sun, W.; Taghizadeh-Hesary, F. Digital Finance, Green Technological Innovation and Energy-Environmental Performance: Evidence from China's Regional Economies. *J. Clean. Prod.* **2021**, *327*, 129458. [CrossRef]
51. Zhong, S.; Li, A.; Wu, J. How Does Digital Finance Affect Environmental Total Factor Productivity: A Comprehensive Analysis Based on Econometric Model. *Environ. Dev.* **2022**, *44*, 100759. [CrossRef]
52. Färe, R.; Grosskopf, S.; Lovell, C.A.K.; Pasurka, C. Multilateral Productivity Comparisons When Some Outputs Are Undesirable: A Nonparametric Approach. *Rev. Econ. Stat.* **1989**, *71*, 90–98. [CrossRef]
53. Chambers, R.G.; Chung, Y.; Fare, R. Profit, Directional Distance Functions, And Nerlovian Efficiency. *J. Optim. Theory Appl.* **1998**, 351–364. [CrossRef]
54. Chambers, R.G.; Chung, Y.; Fare, R. Benefit and Distance Functions. *J. Econ. Theory* **1996**, 407–419. [CrossRef]
55. Zhou, P.; Ang, B.W.; Wang, H. Energy and CO2 Emission Performance in Electricity Generation: A Non-Radial Directional Distance Function Approach. *Eur. J. Oper. Res.* **2012**, 625–635. [CrossRef]
56. Zhang, N.; Kong, F.; Choi, Y.; Zhou, P. The Effect of Size-Control Policy on Unified Energy and Carbon Efficiency for Chinese Fossil Fuel Power Plants. *Energy Policy* **2014**, *70*, 193–200. [CrossRef]
57. Gao, D.; Li, G.; Yu, J. Does Digitization Improve Green Total Factor Energy Efficiency? Evidence from Chinese 213 Cities. *Energy* **2022**, *247*. [CrossRef]
58. Guo, F.; Wang, J.; Wang, F.; Cheng, Z.; Kong, T.; Zhang, X. Measuring China's Digital Financial Inclusion: Index Compilation and Spatial Characteristics. *China Econ. Q.* **2020**, *19*, 1402–1418.
59. Lin, B.; Xu, B. R&D Investment, Carbon Intensity and Regional Carbon Dioxide Emissions. *J. Xiamen Univ. Sci.* **2020**, 70–84.
60. Aw, B.Y.; Roberts, M.J.; Xu, D.Y. R&D Investment, Exporting, and Productivity Dynamics. *Am. Econ. Rev.* **2011**, *101*, 1312–1344. [CrossRef]
61. Qian, H.; Tao, Y.; Cao, S.; Cao, Y. Theoretical and Empirical Analysis on the Development of Digital Finance and Economic Growth in China. *J. Quant. Technol. Econ.* **2020**, 26–46. [CrossRef]
62. Xu, X.; Mu, M.; Wang, Q. Recalculating CO2 Emissions from the Perspective of Value-Added Trade: An Input-Output Analysis of China's Trade Data. *Energy Policy* **2017**, *107*, 158–166. [CrossRef]
63. Zhang, X.; Bao, K.; Liu, Z.; Yang, L. Digital Finance, Industrial Structure, and Total Factor Energy Efficiency: A Study on Moderated Mediation Model with Resource Dependence. *Sustainability* **2022**, *14*, 14718. [CrossRef]
64. Bartik, T.J. How Do the Effects of Local Growth on Employment Rates Vary With Initial Labor Market Conditions? *Upjohn Work. Pap. J. Artic.* **2006**, 1–35. [CrossRef]
65. Yi, X.; Zhou, L. Does Digital Financial Inclusion Significantly Influence Household Consumption? Evidence from Household Survey Data in China. *J. Financ. Res.* **2019**, 47–67.
66. Stock, J.H.; Yogo, M. Testing for Weak Instruments in Linear IV Regression. 2002. Available online: https://www.nber.org/papers/t0284 (accessed on 18 February 2023).
67. Meng, X.; Wu, C. Research on the Impact of Digital Finance on Regional Innovation Ecosystem. *China Soft Sci.* **2022**, 161–171.
68. Mu, X.; Sheng, Z.; Zhao, T. The Impact of China's Digital Financial Development on the Optimization and Upgrading of Industrial Structure. *Econ. Probl.* **2019**, 10–20. [CrossRef]

69. Ren, S.; Hao, Y.; Xu, L.; Wu, H.; Ba, N. Digitalization and Energy: How Does Internet Development Affect China's Energy Consumption? *Energy Econ.* **2021**, *98*. [CrossRef]
70. Mao, C.; Yang, G.; Fan, R. Digital Finance and the Transformation and Upgrading of Industrial Structure in Resource-Based Regions: Empirical Analysis Based on 109 Resource-Based Cities. *Econ. Probl.* **2022**, 63–70. [CrossRef]