frontiers in Energy Research

ORIGINAL RESEARCH
published: 22 December 2020
doi: 10.3389/fenrg.2020.598141

Innovation or Introduction? The Impact of Technological Progress Sources on Industrial Green Transformation of Resource-Based Cities in China

Wancheng Xie[1], Taihua Yan[1], Senmao Xia[2] and Fengzhang Chen[3]*

[1]School of Economics and Business Administration, Chongqing University, Chongqing, China, [2]Business School, Coventry University, Coventry, United Kingdom, [3]College of Computer Science, Chongqing University, Chongqing, China

With the increasingly prominent problems of global resource consumption and environmental pollution, industrial green transformation has become one of the requirements of China's industrial development in the new era. However, there is a lack of research on the impact of technological innovation and technology introduction on the industrial green transformation of resource-based cities. To bridge this gap, this study uses the panel data of 115 resource-based cities in China from 2003 to 2016, and uses the dynamic panel generalized method of moments (GMM) estimation method to study the impact of technological innovation and technology introduction on industrial green transformation of resource-based cities. The results show that technology introduction has a negative effect on the industrial green transformation of resource-based cities, while technological innovation can have a positive effect. Meanwhile, technology introduction has imparted a greater role to technological innovation in promoting this transformation. In addition, the interactive effects between technological innovation and technology introduction have obvious heterogeneity on the industrial green transformation of different types of resource-based cities. Therefore, resource-based cities should continue to increase investment in scientific research, to constantly improve and consolidate their technological innovation ability, optimize foreign investment strategy in technology introduction, and strengthen the digestion and absorption of imported technology, while increasing technological innovation and personnel training.

Keywords: technological innovation, China, technology introduction, industrial green transformation, resource-based cities

Edited by:
Jing Meng,
University College London, United Kingdom

Reviewed by:
Mengqiu Cao,
University of Westminster, United Kingdom
Wei Wang,
Nanjing University, China

****Correspondence:***
Taihua Yan
yantaihua@cqu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *23 August 2020*
Accepted: *12 October 2020*
Published: *22 December 2020*

Citation:
Xie W, Yan T, Xia S and Chen F (2020) Innovation or Introduction? The Impact of Technological Progress Sources on Industrial Green Transformation of Resource-Based Cities in China. Front. Energy Res. 8:598141. doi: 10.3389/fenrg.2020.598141

INTRODUCTION

The Sustainable Development Goals (SDGS) aim to integrate the three dimensions of social, economic, and environmental development from 2015 to 2030, and enable sustainable development (United Nations, 2015). Among them, the goal of SDG7 is to "ensure that all people have access to affordable, reliable, and sustainable modern energy." To achieve this goal, it is necessary to improve energy efficiency and accelerate industrial transformation (Adom and Adams, 2020). After 40 years of reform and opening up, despite the rapid development of its economy and remarkable achievements, environmental problems have always plagued China. China's long-term implementation of an extensive economic growth model, characterized by labor-intensive and resource-intensive production methods (Yi et al., 2013), has caused various environmental problems and hindered sustainable development. The Chinese government has realized the importance of maintaining a balance between the environment and the economy. To achieve the SDG7 goals, China must increase investment in clean energy technology research and upgrade its industrial structure rapidly. Therefore, both the National 13th Five-Year Plan (FYP) and the "Made in China 2025 Plan" (The State Council of the People's Republic of China, 2015), announced the acceleration in developing an ecological civilization and promoting green industrial development. As per the "Industrial Green Development Plan (2016–2020)" (Ministry of Industry and Information Technology, 2016), by 2020, the concept of green development will become the development goal of the whole industry. This will vigorously promote energy efficiency improvement and substantially reduce pollution emissions. The implementation of these measures has effectively promoted the development of clean energy in China. However, according to the world environmental performance index (EPI) ranking in 2018 (Environmental Performance Index, 2018), China scored 50.74 points, ranking 120th among 180 countries in the world, indicating that improving the environment remains China's top priority.

In the past few decades, resource-based cities have played an important role in China's economic growth (Long et al., 2013). According to the National Sustainable Development Plan of Resource-based Cities (2013–2020), there are 262 resource-based cities in China (Liu et al., 2020), with 126 prefecture-level cities, accounting for 43.6% of the total. Resource-based cities rely on the development of local resources to achieve economic development (Li et al., 2013), and resource-intensive industries play a leading role in their economies (Yu et al., 2008). Resource-based cities tend to have higher unemployment rates (Chen et al., 2018b), single employment structure (Tan et al., 2016), lack of growth potential (Li et al., 2013), weak alternative industries (He et al., 2017), lower social insurance (Bo and Hasnat, 2017), and other social and economic problems. Meanwhile, overexploitation and inefficient resource utilization also cause environmental pollution and ecological risks (Ma et al., 2018). However, resource-based cities face more severe crizes in industrial green transformation than do other cities (Yu et al., 2016), which is a global concern. Industry is a major contributor to the economic development of China's resource-based cities, and the major source of environmental pollution. Industrial green transformation is crucial in achieving the sustainable development of resource-based cities (Yuan et al., 2020).

Industrial green transformation refers to improving the efficiency of energy resource utilization, reducing pollutant emissions, reducing environmental impact, improving labor productivity, and enhancing sustainable development capabilities to achieve a win–win situation for both the economy and the environment (Chinese Academy of Social Sciences, 2011). Technological progress is the process of continuous technological development, improvement, and the continuous replacement of old technologies with new ones, which increase energy efficiency and use less polluting technologies in the production process (Kaika and Zervas, 2013). Technological progress is the core of energy efficiency improvement and energy savings (Li and Lin, 2018), and essential for stimulating industrial green transformation. Simultaneously, technological innovation (Guo et al., 2017) and technology introduction (Yang et al., 2017) are the two main paths of technological progress. Technological innovation mainly refers to indigenous innovation (Fu et al., 2011), achieved by increasing scientific research and R&D investment. Technology introduction refers to the acquisition of advanced technical knowledge or equipment from abroad through international technical exchanges and transfers. Developing countries mainly achieve technology introduction through foreign direct investment (FDI). However, there is no consistent conclusion on the role of technological innovation and technology introduction on industrial green transformation.

In the long term, increasing technological innovation input, technological innovation output, and technology introduction are important ways to promote production technology progress (Hu et al., 2020b). In some cases, the input and output of technological innovation and the introduction of technology may not promote the progress of production technology significantly. In other ways, it may not necessarily promote the industrial green transformation of resource-based cities. This is because of the many uncertain intermediate links among the input, output, and technological innovations to the formation of production technology capacity. In terms of technological innovation, on the one hand, there is opportunity cost in technological innovation. The increase in technological innovation input means that the capital invested in production decreases. Therefore, reduced productive investment means reduced output, which may hinder industrial green transformation. In contrast, the high wages of foreign-funded enterprises attract the technical personnel of domestic enterprises and foreign-funded enterprises to merge and participate in domestic enterprises, inducing the R&D investment of the government and enterprises to foreign-funded technology research and development. Therefore, it is not conducive to the improvement of production technology of domestic enterprises, and cannot effectively promote the industrial green transformation of resource-based cities. In terms of technology introduction, local technology, imported technology, and their matching degree will seriously restrict the role of imported technology in the industrial green transformation of resource-based cities. Furthermore, the absorption and digestion capacity determine whether the imported technology can eventually form production technology. Simultaneously, the technology gap is also an important factor, restricting the role of introduced technology in the industrial green transformation of resource-based cities. If the technology gap is too large and the learning ability of the technology importer is low, it will be difficult for local companies to learn. This will result in the hollowing out of imported technology and reduce the level of industrial green transformation.

The above research showed that technological progress could improve the utilization efficiency of natural resources, which is a significant factor in facilitating the industrial green transformation of resource-based cities. However, technological innovation and technology introduction must reflect in the progress of production technology to do so. Therefore, it is necessary to explore the influence of technological innovation and technology introduction on industrial green transformation of resource-based cities. This study examines the impact of technological innovation and technology introduction in detail, which not only has important theoretical significance but also provides valuable decision-making reference in choosing the path of technological progress to achieve industrial green transformation and sustainable development in such cities.

This study contributes to the literature in several ways. First, many existing studies focus on the relationship between a single source of technological progress and industrial green transformation. Guo et al. (2017) studied the impact of technological innovation and regional green performance, and Jin et al. (2019) studied the impact of technological innovation and green total factor efficiency of industrial water resources. Hu et al. (2018) studied the impact of foreign investment and industrial green technology progress. There is no consensus on the impact of technological innovation and technology introduction on industrial green transformation. This present study examines the impact of technological innovation and technology introduction on industrial green transformation. Meanwhile, by constructing the multiplicative term of technological innovation and foreign investment, this study examines the effect of the interaction between technological innovation and technology introduction on industrial green transformation and judges the technological innovation path to promote industrial green transformation. Second, in terms of industrial green transformation, most studies use regional-level (national or provincial)[1] and industry-level data, while some quantitative studies examine cities. For example, Fu et al. (2018) and Chen et al. (2016) measure the dynamic efficiency of industrial green transformation in 30 Chinese mainland provinces. Cheng and Li (2018) empirically test the effects of R&D investment on the green growth of China's manufacturing industry. Simultaneously, resource development creates resource-based cities, and the problem of industrial sustainable development is more prominent than in other cities. Hence, it is more important to study the industrial green transformation of resource-based cities. Therefore, this study uses the panel data of 115 resource-based cities in China from 2003 to 2016 for its research objective. Finally, according to the different stages and the sustainable development ability of resource-based cities, it investigates the heterogeneity of technological innovation and technology introduction on the industrial green transformation of different types of resource-based cities.

This article proceeds as follows: *Literature Review* offers a literature review. *Materials and Methods* introduces the research materials and methods. *Empirical Results and Discussion* contains the empirical results and discussion. Finally, *Conclusion* summarizes the findings and discusses the policy implications of the conclusions.

[1]According to the Constitution of the People's Republic of China, China's administrative regions are divided into four levels. First-level provincial administrative regions include provinces, autonomous regions, and municipalities. Second-level prefecture-level administrative regions include prefecture-level cities and regions. Third-level county-level administrative districts include municipal districts, county-level cities, and counties. Fourth-level township administrative districts include streets and towns.

LITERATURE REVIEW

Impacts of Technological Innovation on Industrial Green Transformation

Many studies consider that technological innovation can promote industrial transformation or industrial green transformation. According to the "Porter hypothesis" (Porter, 1991), technological innovation is mainly to improve resource utilization efficiency through technological progress, thereby promoting industrial green transformation. Simultaneously, "creative destruction" considers that the key to obtain new competitive advantage is to transform through technological innovation (Schumpeter, 1934, p. 10). If an enterprise wants to maintain its competitive advantage, it must constantly perform technological innovation (Veliyath and Shrivastava, 1996). Technological innovation is a continuous source of sustainable development of the contemporary economy and plays a key role in improving resource efficiency and upgrading industrial structure (Ngai and Pissarides, 2007). Some scholars have also shown that advanced technology is conducive to the efficient and clean utilization of energy resources (Yang and Wang, 2013). For example, technological innovation can promote the resource utilization efficiency of both traditional and emerging industries (Miao et al., 2018). In addition, technological innovation plays an important role in promoting the green development of regional economy (OECD, 2011b). Guo et al. (2017) reported that technological innovation has a positive impact on regional green efficiency. Miao et al. (2017) reported that the development of green new products has a major positive effect on the efficiency of natural resource utilization. Therefore, technological innovation can promote the industrial green transformation of resource cities by improving the production technology of traditional industries and increasing the efficiency of resource utilization (Li and Lin, 2018). However, some scholars argue that technological innovation has a negative influence on promoting industrial green transformation. Zhao and Jing (2014) reported that the crowding out effect of technological innovation might shrink enterprises, thereby reducing the efficiency of enterprise resource utilization. Jin et al. (2019) reported that technological innovation has an obvious restraint on the green development of industrial water resources in western China. The above research shows that technological innovation may promote the industrial green transformation of resource-based cities; however, it may also inhibit this process.

Impacts of Technology Introduction on Industrial Green Transformation

Foreign direct investment (FDI) is an important route of technology introduction (Blomstrom and Kokko, 2001). The path of technology introduction through FDI accelerates the transfer of knowledge, technology, and management experience from the home country to the host country (Azman-Saini et al., 2010). Many scholars believe that developing countries have reversed their lack of technological innovation in the early stages of development by using the technology spillover effect of FDI (Barrell and Pain, 1999). Meanwhile, the "Pollution Halo Hypothesis" (Birdsall and Wheeler, 1993) holds that FDI can bring more environment-friendly production standards and technologies to developing countries. FDI has a positive impact on the industrial and ecological environment of host countries through the demonstration effect (List et al., 2003), which means that it is conducive to the productivity improvement, economic growth, and sustainable social development of the host country (Kokko, 1994). Therefore, resource-based cities promote industrial green transformation through the knowledge and technology spillover effects of technology introduction (Doytch and Narayan, 2016). Some scholars have conducted empirical research on this position. For example, Antweiler et al. (2001) reported that FDI is conducive to the improvement of clean technology and green technology in host countries. Albornoz et al. (2009) found that local enterprises in Argentina could improve environmental protection technology by constantly learning and absorbing the advanced environmental management systems of foreign-funded enterprises. Examining the manufacturing industry in China, Hu et al. (2018) found FDI that has a positive spillover effect on the progress rate of green technology.

However, another view holds that technology introduction cannot promote urban economic development and industrial green transformation. The "Pollution Haven Hypothesis" (Cole, 2003) states that relatively developed economies will transfer pollution-intensive enterprises to less developed economies due to the relatively intensive labor force (Taylor and Scott, 2005) and relatively lax environmental regulations in developing countries (Mulatu et al., 2010). These factors cause environmental pollution in developing countries. The empirical results show that the degree of technological development (Dean et al., 2009), strictness of environmental regulation (Kheder and Zugravu, 2012), richness of resources (Dam and Scholtens, 2012) of the host country, and the motivation of multinational enterprises (Rezza, 2013) are the determinants of the pollution refuge hypothesis. China's resource-based cities have abundant resources and low-standard environmental regulations, which may cause the introduction of technology to hinder the industrial green transformation. Jorgenson (2009) studied less developed countries and reported that FDI in the manufacturing sector is positively correlated with industrial water pollution. Meanwhile, scholars have reported that multinational companies transfer pollution-intensive production to developing countries (Chung, 2014), causing serious pollution and inhibiting the green transformation of industry (Acharyya, 2009). In addition, Yan et al. (2019) found the greater foreign investment a resource-based city receives, the lower its energy and technology efficiency. These results show that FDI will have a negative impact on the environment of host countries, which means that technology introduction is not conducive to industrial green transformation in the region. The above research shows that technology introduction may both promote and inhibit the industrial green transformation of resource-based cities.

Measurement of Industrial Green Transformation

Owing to unsustainable industrial development in China in recent years, and increasing resource and environmental problems, industrial green development has gradually become a research hotspot. The characteristics of industrial production activities necessitate that scholars focus on the adverse effects on the environment without losing sight of the potential economic benefits of industry (Zhou et al., 2013). Industrial green transformation will resolve the problems in the industrial development process, such as high energy consumption, heavy environmental pollution, low production efficiency, and weak international competitiveness (Van de Kerk and Manuel, 2008). The region needs an environment-friendly and resource-saving society. This is also the embodiment of a "green economy" (Pearce et al., 1989) in the industrial industry. Improving the efficiency of industrial green transformation is the key to achieving the green development of industry (Pearce, 2013). Consequently, improving the green transformation level of resource-based cities is the key to achieving sustainable development.

Today, more scholars are focusing on the measurement of industrial green transformation. The following technical methods are common for measuring the green transformation of industry. Chen et al. (2016) used the analytic hierarchy process (AHP) to construct an evaluation index system to evaluate the green development of China's industry. Feng et al. (2017) measured the efficiency of China's regional industrial green transformation by combining the hybrid model and window analysis. In addition, many scholars used the data envelopment analysis (DEA) method to study industrial green transformation issues. Cheng and Li (2018) used the nondirectional distance function (NDDF) and meta-frontier methods to measure green growth in China's manufacturing industry. The Organization for Economic Cooperation and Development (OECD) has established a complete green development index system covering all aspects of economy, environment, and human well-being (OECD, 2011a). Li et al. (2016) used the DEA model to evaluate the sustainable development of resource-based cities. Hu et al. (2020a) used the hyperbolic distance function (HDF) model to measure the energy and environment performance of resource-based cities. Hu et al. (2019) used the Super-slack based measure (SBM) function and the Global Malmquist–Luenberger (GML) index to calculate China's manufacturing industrial green total factor productivity.

In general, the above studies adopt a single index to depict technological progress, and do not consider the difference in the effects of different sources of technological progress on industrial green transformation. The new economic growth theory believes that technological innovation can accumulate knowledge and promote process innovation, which provides a steady stream of power and support for sustainable economic growth (Jefferson et al., 2006). International trade theory holds that through the introduction, digestion, and absorption of advanced technologies from developed countries, developing countries could accelerate economic growth and industrial green transformation (Corssman and Helpman, 1991). Combined with the existing theoretical framework, this study analyses the impact of technological innovation and technology introduction on the industrial green transformation of resource-based cities. Simultaneously, this study analyzes the effect of the interaction between technological innovation and technology introduction on industrial green transformation of resource-based cities.

MATERIALS AND METHODS

Model Setting

Global Malmquist–Luenberger Measure for Determining the Green Growth Index

This study focuses on the measurement of industrial green transformation of resource-based cities. [2]The investigators considered the Super-SBM directional distance function of unanticipated outputs, and used the GML index to measure the industrial green transformation of resource-based cities. In empirical applications, existing research uses the GML index to measure the green total factor productivity of the industrial sector (Wang et al., 2020), China's industrial green productivity (Wang and Shen, 2016), and light manufacturing industries (Emrouznejad and Yang, 2016). Meanwhile, the traditional Malmquist–Luenberger (ML) index has two potential disadvantages over the GML index. First, the industrial green transformation measured by the traditional ML index has no multiplicative property. The traditional ML index can only analyze the short-term fluctuations of production efficiency in adjacent periods; it cannot observe the long-term growth trend of production efficiency. This may lead to "technical regression," which is obviously unreasonable. Second, the mixing direction of the SBM function, the output reduction, and the output reduction of the undesired output may lead to infeasible solutions. However, GML indexing can avoid the shortcomings of infeasible solution. The GML index is based on a set of production possibilities over the full-time horizon of all decision-making units (Hu et al., 2019). Therefore, this study chooses the GML index to measure the industrial green transformation of resource-based cities.

Production Possibility Set Considering Environmental Factors

This study assumes that each resource-based city is a decision unit and set as DMU_K, where K represents the number of prefecture-level cities in resource-based cities. $x = (x_1, \ldots, x_n)$ represents N production essentials put into each region, where $x \in R_N^+$, obtain M expected outputs, $y = (y_1, \ldots, y_n) \in R_M^+$, I non-anticipated outputs, $b = (b_1, \ldots, b_n) \in R_I^+$, and x^{kt}, y^{kt}, b^{kt} represent the input and output in the T phase; the production frontier of the DEA's unexpected output can be expressed as follows:

$$P^t(x) = \left\{ \begin{array}{c} (y^t, b^t) : \sum_{k=1}^{K} z_k^t y_{km}^t \geq y_{km}^t,\ \forall m;\ \sum_{k=1}^{K} z_k^t b_{ki}^t = b_{ki}^t,\ \forall i; \\ \sum_{k=1}^{K} z_k^t x_{kn}^t \leq x_{kn}^t,\ \forall n; \sum_{k=1}^{K} z_k^t = 1, z_k^t \geq 0, \forall k \end{array} \right\} \tag{1}$$

where z_k^t represents the weight of the observations of each cross section. However, there will be production technology retrogression in the $P^t(x)$ model. To avoid this, some scholars built a global production possibility set $P^G(x)$ based on $P^t(x)$, which emphasizes the consistency and comparability of the production frontier (Oh, 2010). The model is as follows:

$$P^G(x) = \left\{ \begin{array}{c} (y^t, b^t) : \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t y_{km}^t \geq y_{km}^t,\ \forall m; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t b_{ki}^t = b_{ki}^t,\ \forall i; \\ \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t x_{kn}^t \leq x_{kn}^t,\ \forall n; \sum_{t=1}^{T} \sum_{k=1}^{K} z_k^t = 1, z_k^t \geq 0, \forall k \end{array} \right\} \tag{2}$$

Global Super-Slack Based Measure Directional Distance Function

The investigators defined the direction distance function in the energy environment (Fukuyama and Weber, 2009) as follows:

$$\begin{aligned} &\overrightarrow{S_V^t}\left(x^{t,k}, y^{t,k}, b^{t,k}, g^x, g^y, g^b\right) = \max_{s^x, s^y, s^b} \frac{\frac{1}{N}\sum_{n=1}^{N} \frac{S_n^x}{g_n^x} + \frac{1}{M+I}\left(\sum_{m=1}^{M} \frac{S_m^x}{g_m^x} + \sum_{i=1}^{I} \frac{S_i^b}{g_i^b}\right)}{2} \\ &\text{s.t.} \sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^t,\ \forall n; \sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^t, \forall m; \\ &\sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \forall i;\ \sum_{k=1}^{K} z_k^t = 1,\ z_k^t \geq 0,\ \forall k;\ s_m^y \geq 0,\ \forall m;\ s_i^b \geq 0,\ \forall i \end{aligned} \tag{3}$$

In **Eq. (3)**, g^x represents the direction vector of input reduction, g^y represents the direction vector of expected output increase, and g^b represents the direction vector of non-expected output decrease; s_n^x represents the input redundant relaxation vector, s_m^y represents the expected output insufficient relaxation vector, and s_i^b represents the unexpected output excessive relaxation vector. Similarly, the Global SBM direction distance function is as follows:

[2]According to sustainable development plan of resource-based cities in China (2013–2020) issued by the State Council, resource-based cities are those in which the mining and processing of natural resources, such as minerals and forests in the region, are the leading industries (including prefecture-level cities, districts, and other county-level administrative districts). In all, there are 262 resource-based cities, including 126 prefecture-level administrative regions, 62 county-level cities, 58 counties, and 16 municipal districts. Available online at: http://www.gov.cn/zwgk/2013-12/03/content _2,540,070.htm.

$$\overrightarrow{S_V^G}\left(x^{t,k}, y^{t,k}, b^{t,k}, g^x, g^y, g^b\right) = \max_{s^x,s^y,s^b} \frac{\frac{1}{N}\sum_{n=1}^{N}\frac{S_n^x}{g_n^x} + \frac{1}{M+I}\left(\sum_{m=1}^{M}\frac{S_m^x}{g_m^x} + \sum_{i=1}^{I}\frac{S_i^b}{g_i^b}\right)}{2}$$

$$\text{s.t.} \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^t, \forall n; \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^t, \forall m;$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \forall i; \sum_{k=1}^{K} z_k^t = 1,\ z_k^t \geq 0,\ \forall k;\ s_m^y \geq 0,\ \forall m;\ s_i^b \geq 0,\ \forall i \tag{4}$$

Global Malmquist–Luenberger Indicator (GML)

This study constructs the GML index (*Gtfp*) through directional distance function SBM to overcome the disadvantage of the ML index often having no solution when solving linear programming. The GML index is further divided into the technical efficiency (*Geffch*) index and technical progress (*Gtech*) index. The specific decomposition of the model is as follows:

$$Gtfp_t^{t+1} = \frac{1 + \overrightarrow{S_V^G}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)}{1 + \overrightarrow{S_V^G}\left(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b\right)} = geffch_t^{t+1} \times gtech_t^{t+1} \tag{5}$$

$$geffch_t^{t+1} = \frac{1 + \overrightarrow{S_V^t}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)}{1 + \overrightarrow{S_V^{t+1}}\left(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b\right)} \tag{6}$$

$$gtech_t^{t+1} = \frac{\left[1 + \overrightarrow{S_V^G}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)\right] \Big/ \left[1 + \overrightarrow{S_V^t}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)\right]}{\left[1 + \overrightarrow{S_V^G}\left(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b\right)\right] \Big/ \left[1 + \overrightarrow{S_V^{t+1}}\left(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b\right)\right]} \tag{7}$$

where the GML index (*Gtfp*) represents the relative change value of $t+1$ based on t period, $\overrightarrow{S_V^t}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)$ and $\overrightarrow{S_V^G}\left(x^t, y^t, b^t; g^x, g^y, g^b\right)$ represent current and Global SBM distance functions, respectively. The GML and its components can be interpreted as follows: i) GML >0 represents the improvement of industrial green transformation; ii) GML < 0 represents the deterioration of industrial green transformation; and iii) GML = 0 represents that industrial green transformation has not changed.

Existing literature generally believes that changes in industrial green technology should be measured by changes in total factor productivity, and usually decomposes GML into technological changes and efficiency changes based on the measurement principle. The change in industrial technology may not only occur from the absorptive capacity of foreign technology and a good foreign production management system but also manifest in the introduction of new technology and technological innovation. Hence, this study considers the GML index to measure industrial green transformation.

Empirical Model

Technological innovation and technology introduction are two important factors influencing the industrial green transformation of resource-based cities. To study the influence of technological innovation and technology introduction on the efficiency of industrial green transformation, this study constructed an econometric model of efficiency and influencing factors of green transformation in resource-based cities as follows:

$$\mathrm{GML}_{it} = \alpha_0 + \alpha_1\mathrm{TI}_{it} + \alpha_2\mathrm{FTI}_{it} + \alpha_3\mathrm{PGDP}_{it} + \alpha_4\mathrm{MD}_{it} + \alpha_5\mathrm{HC}_{it} + \alpha_6\mathrm{ER}_{it} + \alpha_7\mathrm{NET}_{it} + c_i + \mu_{it} \tag{8}$$

where i represents industry, t represents the time, c_i is the city individual fixed effect that does not change with time, and μ_{it} represents the error term. The dependent variable is indexing efficiency of industrial green transformation of resource-based cities, that is, GML. The econometric model has the year 2003 as the base period and converts it to a cumulative growth index.

The existing literature usually constructs the multiplicative term of human capital and foreign investment participation (Xu, 2000) or the multiplicative term of R&D and foreign investment participation (Kokko et al., 1996) to test the impact of local learning and absorption capacity on foreign technology spillovers. The absorptive capacity includes not only the ability to absorb foreign technology but also the ability to imitate learning. Therefore, to investigate whether technology introduction will promote the impact of technological innovation on the industrial green transformation of resource-based cities, this study constructs the multiplicative term of technological innovation and technology introduction (TI*FTI). The specific form is as follows:

$$\mathrm{GML}_{it} = \beta_0 + \beta_1\mathrm{TI}_{it} + \beta_2\mathrm{FTI}_{it} + \beta_3\mathrm{TI}_{it}{*}\mathrm{FTI}_{it} + \beta_4\mathrm{PGDP}_{it} + \beta_5\mathrm{MD}_{it} + \beta_6\mathrm{HC}_{it} + \beta_7\mathrm{ER}_{it} + \beta_8\mathrm{NET}_{it} + c_i + \mu_{it} \tag{9}$$

As we know, FTI reflects the digestion, absorption, learning, and imitation of imported technology by local enterprises, and does not focus on the improvement of imported technology. The multiplicative term of technological innovation and technology introduction (TI*FTI) represents the interactive effects of technological innovation and technology. TI*FTI may not only indicate the digestion and absorption of imported technology, and learning and imitation of local enterprises, but also through investment in technological innovation, which increases the digestion and absorption of imported technology, reflecting in the improvement of imported technology. Therefore, TI*FTI includes not only simple imitation but also independent innovation based on introduction and absorption imitation.

Many economic and social phenomena are continuous and interrelated. In the econometric model, the variables are autoregressive and interactive. For example, the present level of industrial green transformation may affect the next level of such transformation. Meanwhile, technological innovation and technology introduction may not only promote industrial green transformation but also may be the result of such transformation. Therefore, it is necessary to solve the endogeneity problem of ordinary panel model estimation. The static panel model **Eqs. (8)** and **(9)** are modified to the dynamic model **Eqs. (10)** and **(11)**, which contain the first order of the explained variables. The final model is as follows:

$$\mathrm{GML}_{it} = \alpha_0 + \varphi\mathrm{GML}_{i,t-1} + \alpha_1\mathrm{TI}_{it} + \alpha_2\mathrm{FTI}_{it} + \alpha_3\mathrm{PGDP}_{it} + \alpha_4\mathrm{MD}_{it} + \alpha_5\mathrm{HC}_{it} + \alpha_6\mathrm{ER}_{it} + \alpha_7\mathrm{NET}_{it} + c_i + \mu_{it} \tag{10}$$

TABLE 1 | Parameters of industrial green transformation.

Variable classification	Variable symbol	Variable definitions
Factor input	LCI	Sum of the number of mining industry employees, manufacturing industry employees, power gas and water supply employees
	CS	Total fixed assets of industrial enterprises
	IEC	Industrial electricity consumption
	IWC	Industrial water consumption
Expected output	GIO	Gross value of industrial output
Unexpected output	SE	Industrial smoke and dust emissions
	DE	Industrial sulfur dioxide emissions
	WE	Industrial wastewater emissions

$$\begin{aligned}\mathrm{GML}_{it} = \beta_0 + \tau\mathrm{GML}_{i,t-1} + \beta_1\mathrm{TI}_{it} + \beta_2\mathrm{FTI}_{it} + \beta_3\mathrm{TI}_{it}*\mathrm{FTI}_{it} \\ + \beta_4\mathrm{PGDP}_{it} + \beta_5\mathrm{MD}_{it} + \beta_6\mathrm{HC}_{it} + \beta_7\mathrm{ER}_{it} + \beta_8\mathrm{NET}_{it} \\ + c_i + \mu_{it}\end{aligned} \tag{11}$$

Variable and Definition

Industrial Green Transformation

We use the GML index to measure the industrial green transformation of resource-based cities. According to traditional economic growth theory, the basic variables of production function are capital, labor, technology, and output level. However, Weitzman (1995) considers that economic growth mainly includes human capital, physical capital, and natural capital, and proposes that the environment is an important natural capital. This present study considers the rigid constraints of resources and environment of resource-based cities on the scale and speed of industrial economic development, and includes resources and environment in the analysis frame of industrial economic growth. Hence, the investigators constructed the correlative indexes of the expected output, unexpected output, and factor inputs as follows:

Factor inputs: Labor capital investment (LCI), scholars generally use the annual average number of industrial employees to measure, considering that the industrial sector mainly includes the mining industry, manufacturing industry, power, gas and water production, and supply industry. This study uses the sum of the number of mining industry employees, manufacturing industry employees, power gas, and water supply employees (Zhang, et al., 2011) to measure industrial labor input. For capital stock (CS), the investigators used the total fixed assets of industrial enterprises above a designated size for measurement. For energy input (EI), considering that energy consumption and water resource consumption are not the main sources of expected output and it is difficult to obtain the total energy consumption of industry, this study used industrial electricity consumption (IEC) and industrial water consumption (IWC) for the measurement. Expected output: This study sets the gross value of industrial output (GIO) as expected output. Unexpected output: considering the prominent problems of air pollution and water pollution due to industrial development, to measure industrial green transformation comprehensively, the investigators selected industrial smoke and dust emissions (SE), industrial sulfur dioxide emissions (DE), and industrial wastewater emissions (WE) as the unexpected output. **Table 1** summarizes the parameters of industrial green transformation.

Independent Variable

Technological progress is the core driving force in improving the industrial green transformation of resource-based cities. In the long term, the main ways to promote production technology are to increase investment in technological innovation, improve the output of technological innovation (such as patents and scientific papers), and increase the strength of technology introduction. Hence, the core independent variables mainly include technological innovation and technology introduction.

1) Technological Innovation: Technological innovation is a basic method of enhancing resource efficiency and upgrading industrial structure. In general, the existing research reflects the measurement of technological innovation in three aspects. 1) Measuring technological innovation from the perspective of technological innovation investment, scholars mainly adopt R&D expenditure and government investment in science and technology (Kontolaimou et al., 2016). 2) Measured from the perspective of technological innovation output, the variables include patent (Griliches, 1990), product innovations (Cruz-Cazares et al., 2013), and process innovations (Akgün et al., 2009). 3) Constructing a comprehensive index to evaluate and measure technological innovation, for example, measuring technological innovation from two aspects of input and output (Guo et al., 2017). This present study considered the availability and representativeness of data comprehensively, and the investigators used the proportion of science and technology investment to GDP (TI) for the measurement.

2) Technology Introduction: Technology introduction mainly consists of three channels as follows: technology trade, import, and FDI. In most cases, technology transfer Congress controls the trade of advanced technology to maintain its monopoly position. Most of the technology transferred through patents is mature and declining technology. Furthermore, information asymmetry makes it difficult for technology purchasers to acquire all technologies. Imported products may obtain more advanced technology than through technology transfer. However, information asymmetry makes it difficult for importing countries to obtain core technologies through "reverse engineering." For FDI, to occupy the investment market, multinational enterprises may adopt advanced technology for production to gain competitive advantage. Simultaneously, employees of multinational enterprises may flow to local enterprises, and local enterprises will absorb and digest relevant technologies to achieve technological progress. Therefore, FDI is an important method of introducing technology (Blomstrom and Kokko, 2001). The technology spillover of FDI will continuously improve the level of clean energy technology and output levels of local enterprises (Perkins and Neumayer, 2008). However, strict foreign environmental regulations and policies may force enterprises with high levels of

TABLE 2 | Variables' definition.

Variable classification	Variable symbol	Variable definitions
GML	Factor input	Labor capital investment, capital stock, energy input
	Expected output	The gross value of industrial output
	Unexpected output	Industrial smoke and dust emissions, industrial sulfur dioxide emissions and industrial wastewater emissions
Independent variable	TI	Ratio of science and technology investment to GDP
	FTI	Ratio of actual FDI to investment in social fixed assets
Control variable	PGDP	Local per capita GDP, take the natural logarithm
	MD	Ratio of urban individual and private economic employees To the total employment
	HC	Ratio of number of higher education to total population
	ER	Urban residents' disposable, take the natural logarithm
	NET	Number of internet users, take the natural logarithm

energy consumption and pollution to move to developing countries (Deng and Xu, 2015). The investigators used the proportion of actual FDI in the fixed investment of the whole society (FTI) for the measurement.

Control Variable

1) Regional economic development level (PGDP): The growth of the economic aggregate would lead to the adjustment of industrial sectors, promote the transformation of industrial structure, and ultimately improve the efficiency of regional industrial green transformation (Song et al., 2013). This present study uses the local per capita GDP as a proxy index to indicate the level of regional economic development, and the form of logarithm to increase the stationarity of data and eliminate any possible heteroscedasticity. 2) Marketization degree (MD): The higher the degree of marketization, the more conducive is the flow of factors of production to industries with high efficiency. This study measures MD by the proportion of urban individual and private economic employees in total employment. 3) Human capital (HC): Human capital is the core element of technological innovation in industrial enterprises, and education is the guarantee of human capital formation. This study uses the ratio of residents with higher education and the total population in the region for the measurement. 4) Environmental regulation (ER): This is an important factor affecting the innovation of green technology. Antweiler et al. (2001) consider it to be highly correlated with residents' income level. Therefore, this study chooses the urban residents' disposable income as the alternative variable, and uses the logarithmic form to increase the stationarity of the data and eliminate any possible heteroscedasticity. 5) Level of information technology (NET): Selecting the number of Internet users as a measure of the level of information technology, the same form of logarithm. **Table 2** summarizes the variables and their definitions.

TABLE 3 | Descriptive statistics.

Variable	*N*	Mean	St. dev	Min	Max
LCI	1,610	105,865	74,542	5,600	449,600
CS	1,610	5,387,745	6,468,444	86,045	64,988,164
IEC	1,610	378,827	526,217	1,016	5,195,783
IWC	1,610	5,670	7,910	74	84,440
GIO	1,610	12,709,053	17,734,412	84,543	153,678,749
SE	1,610	43,105	178,135	139	5,168,812
DE	1,610	4,984	4,339	122	29,365
WE	1,610	64,632	56,122	612	337,164
GML	1,610	1.0211	0.1148	0.5721	1.8343
TI	1,610	0.0015	0.0056	4.03E − 08	0.2089
FTI	1,610	0.0238	0.0302	0	0.2824
PGDP	1,610	9.9644	0.8195	4.5951	12.4564
MD	1,610	0.8390	0.7989	0.0066	18.8056
HC	1,610	0.0081	0.0074	0.00003	0.0531
ER	1,610	9.5888	0.4922	8.1303	10.7319
NET	1,610	11.9935	1.05458	8.2815	14.6220

Data and Descriptive Statistics

Based on the Chinese government's plans in 2013 (Council, 2013), and considering the pertinence of the research, continuity of data availability, and comparability between cities, this study selects the data of 115 resource-based cities in China from 2003 to 2016, with 1,610 observations. We derive the related variables from the China City Statistical Yearbook, the China Environment Statistical Yearbook, and the statistical bulletins of national economic and social development in various cities. Meanwhile, the study also uses dataset sources from the Economy Prediction System (EPS) database.[3] Furthermore, this study uses the interpolation method to complete some missing values in the variables. **Table 3** gives a statistical description of the main variables.

EMPIRICAL RESULTS AND DISCUSSION

Basic Model Regression Results

According to the existing literature, there are two methods for estimating dynamic panel models: the difference-GMM (D-GMM) estimation and the system-GMM (S-GMM) estimation. The weak instrumental variables in the D-GMM estimation process may result in serious limited sample bias. However, the S-GMM estimation was based on the D-GMM estimation, which takes the lagged variable of the difference item as the level value of the instrumental variable. Increasing the number of tool variables can effectively resolve the problem of weak tool variables, and the endogenous problem in the model. Simultaneously, the S-GMM estimation can improve estimation efficiency and estimate variable coefficients that do not change

[3]EPS global statistical data/analysis platform is a professional data service platform founded by Beijing Forecast Information Technology Co., Ltd. The EPS data platform has built a series of professional databases, including World Trade Data, China Industry Business Performance Data, the China City Statistical Yearbook, and the China Environment Statistical Yearbook. Available online at http://olaptest.epsnet.com.cn/

TABLE 4 | Estimation results of dynamic panel model.

Variable	GML			
	(1)	(2)	(3)	(4)
TI	0.473***		0.940**	0.071
	(8.98)		(10.86)	(0.25)
FTI		−0.293***	−0.337***	−0.346***
		(−20.52)	(−13.10)	(−8.55)
TI*FTI				120.456***
				(7.76)
PGDP	0.042***	0.031***	0.446***	0.026***
	(21.3)	(8.22)	(18.27)	(7.31)
MD	0.003**	0.003**	0.002	0.004
	(2.51)	(2.54)	(1.74)*	(1.63)
HC	2.046***	2.201***	1.344***	1.590***
	(20.15)	(10.05)	(10.79)	(10.50)
ER	−0.156***	−0.132***	−0.156***	−0.137***
	(−44.52)	(−24.85)	(−28.99)	(−22.97)
NET	0.028***	0.020***	0.024***	0.024***
	(14.26)	(15.23)	(11.98)	(8.83)
AR (1)	−6.59	−6.590	−6.553	−6.502
	(0.000)	(0.000)	(0.000)	(0.000)
AR (2)	−0.959	−0.907	−1.157	−1.145
	(0.338)	(0.364)	(0.258)	(0.252)
Sargan	107.172	110.609	110.162	98.540
	(0.637)	(0.546)	(0.558)	(0.327)

Notes: The value in brackets is the value of t*.*, **, ***, respectively, indicating that the estimated parameters pass the statistical significance test at the 10, 5, and 1% levels, respectively.*

with time. This study mainly used S-GMM to estimate the dynamic panel model that technological innovation and technology introduction affect the green efficiency of resource-based city industry, with **Table 4** presenting the results.

The diagnosis test shows that the results of AR 1) and AR 2) indicate that the first-order residual has a first-order serial correlation; however, no second-order sequence correlation exists; that is, the S-GMM estimator is consistent. Furthermore, the results of Sargan test prove that the selected instrumental variables are reasonable and effective.

First, this study analyzes the effects of technological innovation on industrial green transformation of resource-based cities. The regression results indicate that technological innovation has a significant positive impact on industrial green development. This is probably because the Chinese government has continuously increased investment in scientific and technological research in recent years to improve the independent innovation capabilities of enterprises. Consequently, technological innovation improves the efficiency of enterprise resource utilization, which promotes the green transformation of industry in resource-based cities. Simultaneously, Chen et al. (2016) also show that technological innovation can promote the green development of China's industry.

Second, the results show that technology introduction has a significant inhibitory effect on the industrial green transformation of resource-based cities. The "Pollution Haven Hypothesis" also proves this conclusion. This can be explained in two parts: 1) resource-based cities in China have cheap resources and immature environmental regulations, which attract foreign investment to their high energy consumption and heavy-polluting industries (Yan et al., 2019) and 2) technology introduction may worsen competing domestic companies, and even crowd them out from the market (Hu and Jefferson, 2002). The competitive pressure from foreign investment has squeezed the market share of local enterprises, reducing their profits and R&D capacity. Consequently, it hinders the technological progress of local enterprises and restricts the industrial green transformation of resource-based cities.

Third, the interactions between technological innovation and technology introduction have significantly increased the industrial green transformation of resource-based cities. The results show that technological innovation induced by technology introduction does benefit to improving the efficiency of industrial green transformation in China's resource-based cities. The increasing investment in scientific research has resulted in technological innovation, which promotes the transformation of green industries in resource-based cities through the absorption and imitation of foreign technologies. Increasing investment in scientific research and technological innovation can improve the technological level of enterprises and reduce the technological gap with foreign-funded enterprises, accelerating the transfer of foreign knowledge, technology, and management experience (Azman-Saini et al., 2010).

In addition, this study also analyzes the impact of other control variables on the industrial green transformation of resource-based cities. The regression results show that 1) the regional economic development level (PGDP) of each model shows a significant positive impact. Cities with high economic development levels tend to have stronger financial resources and can use more resources for the green transformation and development of urban industry (Yan et al., 2019). 2) Marketization degree (MD) is always beneficial in promoting green transformation, and the market competition mechanism helps enterprises change the direction of green production, by

TABLE 5 | Results of the robustness test.

Variable	Technical efficiency (TE)		Technical progress (TP)	
	(1)	(2)	(3)	(4)
TI	0.392***	0.249***	0.713**	0.155
	(12.28)	(3.80)	(4.05)	(0.29)
FTI	−0.032**	−0.080***	−0.396***	−0.350***
	(−3.09)	(−6.92)	(−8.18)	(−9.08)
TI*FTI		58.033***		149.538***
		(13.13)		(5.95)
Controlled variables	Yes	Yes	Yes	Yes
AR (1)	−6.770	−6.790	−7.651	−7.687
	(0.000)	(0.000)	(0.000)	(0.000)
AR (2)	−1.716	−1.708	−1.287	−1.233
	(0.086)	(0.088)	(0.198)	(0.217)
Sargan	106.167	104.419	98.332	107.907
	(0.638)	(0.706)	(0.333)	(0.901)

Notes: The value in brackets is the value of t., **, ***, respectively, indicating that the estimated parameters pass the statistical significance test at the 10, 5, and 1% levels, respectively.*

conforming to market demand. 3) The coefficient before HC is significantly positive in all models. As the central link of green technological innovation, the level of HC has an important role in promoting the green industrial transformation of resource-based cities, indicating that HC is an important source of industrial green efficiency improvement in China. 4) Environmental regulation (ER) has a significant positive effect on industrial green transformation of resource-based cities. Other studies on the relationship between environmental policy and industrial green transformation also give consistent results (Lanoie et al., 2011). There may be two reasons. First, the response of local governments and industries to national environmental regulation may be heterogeneous (Zhu et al., 2014). Second, the poor implementation mode and quality of environmental regulations lead to negative impact on green transformation (Jin et al., 2019). 5) The level of information technology (NET) also has a significant positive effect. An improvement in the level of information technology is conducive to the promotion of industrial green transformation of resource-based cities.

Robustness Test

Due to the GML index cannot effectively consider the impact of technological innovation and technology introduction on the technical efficiency and technological progress in promoting total factor productivity. Consequently, this study uses technical efficiency and technological progress index as explanatory variables to examine the impact of technological innovation and technology introduction regression on the industrial green transformation of resource based. **Table 5** shows the specific results.

Under the significance level of at least 1%, the result shows that the technological innovation coefficient is positive, which indicates that technological innovation promotes the green industrial technical efficiency and technological progress of resource-based cities in China. This also shows that technological innovation promotes the industrial green transformation of resource-based cities by improving industrial technical efficiency and technological progress. Meanwhile, the influence of technology introduction on technical efficiency and technological progress is significantly negative. It passes the significance test at the 1% level, indicating that technology introduction will increase the negative influence on technical efficiency and technological progress at the present stage, which is also consistent with previous conclusions. Thus, technology introduction does not bring obvious knowledge and technology spillovers (Li et al., 2017) to resource-based cities. Finally, under the 1% significance level, the interactions between technological innovation and technology introduction promote the improvement of technical efficiency and technological progress of industrial green transformation. This shows that technology introduction can increase the impact of technological innovation on the technical efficiency and technological economy of industrial green transformation. Local enterprises have promoted the improvement in efficiency of the green transformation of resource-based cities by digesting and absorbing technology. This is also consistent with previous conclusions. In conclusion, the sign and significance level of regression coefficients of main variables are essentially the same as the basic model, which proves that the above results are robust.

Heterogeneity Test

According to the "Plan of Sustainable Development for Resource-based Cities in China (2013–2020)" (Council, 2013) issued by the State Council of China, the leading industries of resource-based cities mainly exploit and process natural resources such as minerals and forests in the region. Simultaneously, the state divides resource-based cities into growth-type, maturity-type, recession-type, and regeneration-type, according to the resource support capacity and sustainable development ability. Therefore, according to this classification, this study tests the heterogeneity of technological innovation and technology introduction on the industrial green transformation of different resource-based cities. **Table 6** shows that the result of AR (1), AR (2), and Sargan tests in all models pass the test

TABLE 6 | Results of the heterogeneity test.

Variable	Growth-type		Maturity-type		Recession-type		Regeneration-type	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TI	15.424*	−48.127	9.185***	−2.229***	43.718*	17.201**	2.496	−128.541
	(1.65)	(−0.27)	(11.62)	(−7.77)	(1.85)	(2.42)	(0.37)	(−1.92)*
FTI	3.780	−9.839	−0.054	−0.206***	−0.183	−0.663	0.644*	−3.708
	(0.78)	(−1.06)	(−0.59)	(−3.43)	(−0.18)	(−1.13)	(1.69)	(−1.64)*
TI*FTI		4,643.689		195.43***		−579.049*		3,270.301*
		(1.01)		(9.73)		(−1.76)		(1.99)
Controlled variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AR (1)	−2.00	−1.75	−5.11	−5.179	−2.13	−2.69	−6.49	−1.81
	(0.045)	(0.080)	(0.000)	(0.000)	(0.033)	(0.007)	(0.000)	(0.071)
AR (2)	0.58	1.25	−0.86	−0.559	0.12	−2.17	−0.05	−0.13
	(0.563)	(0.212)	(0.387)	(0.576)	(0.908)	(0.030)	(0.963)	(0.899)
Sargan	164.70	100.67	56.98	54.759	281.77	33.62	134.47	97.38
	(0.341)	(0.300)	(0.476)	(0.597)	(0.242)	(0.630)	(0.104)	(0.385)

Notes: The value in brackets is the value of t., **, ***, respectively, indicating that the estimated parameters pass the statistical significance test at the 10, 5, and 1% levels, respectively.*

conditions, indicating that the design of the model is reasonable, and the estimation using the system GMM is effective.

In **Table 6**, the coefficients of different types of resource-based cities before technological innovation are positive, indicating the importance of increasing investment in scientific and technological research and development for the sustainable development of resource-based cities. Therefore, technological innovation can promote the industrial green efficiency of different types of resource-based cities. This proves that increasing investment in technological innovation and promoting production technology are important methods to promote such green transformation in China. In terms of technology introduction, different types of resource-based cities show strong heterogeneity. The technology introduction coefficient of renewable resource-based cities is significantly positive, indicating that renewable resource-based cities can significantly improve the efficiency of regional industrial green transformation. Since regeneration-type essentially eliminates resource dependence, they also have higher levels of opening up and technological innovation. Therefore, renewable resource-based cities can improve the production technology and energy efficiency of local enterprises through foreign technology spillovers. The interactions between technological innovation and technology introduction show significantly positive coefficients of regeneration-type and maturity-type resource-based cities. However, the coefficient before the interactions between technological innovation and technology introduction of recession-type resource-based cities is significantly negative. The results show that technological innovation induced by technology introduction is not conducive to the industrial green transformation improvement. Recession-type cities face problems of resource depletion and relatively backward economic development. This may lead to vicious competition between foreign-funded enterprises and local enterprises, and this may not be conducive to the improvement of regional industrial green efficiency. The above analysis shows that the impact of technological innovation and technology introduction of different types of resource-based cities in China on industrial green transformation has strong heterogeneity.

CONCLUSION

Based on the panel data of 115 resource-based cities in China from 2003 to 2016, this study uses the S-GMM method to empirically analyze the impact of technological innovation and technology introduction on the industrial green transformation of resource-based cities. We draw the following conclusions:

First, technological innovation can improve the level of industrial green transformation of resource-based cities in China. In recent years, the government has continuously increased investment in scientific research, enabling enterprises to improve existing production technologies, energy-conserving techniques, and carbon-reduction technologies (Li et al., 2017). Consequently, energy efficiency improves, pollutant emissions reduce, and the industrial structure optimizes (Wang et al., 2011), which stimulates the industrial green transformation of resource-based cities. Simultaneously, it is necessary for China to implement science and technology innovation strategies and improve regional technological innovation. This study contributes to research on clean energy technologies in resource-based cities, including solar energy, renewable energy, and more advanced and cleaner fossil fuels, which promote the energy efficiency and industrial green transformation of resource-based cities. This discovery also provides a feasible path for industrial green transformation of resource-based cities in developing countries around the world.

Second, technology introduction inhibits the improvement of industrial green transformation level in resource-based cities. There are three possible reasons for this result. 1) Lax environmental regulation in resource-based cities attracts polluting foreign capital (Zhang and Zhou, 2016). This increases the need for energy consumption in resource-based cities, which hinders their green transformation. 2) Foreign investment would employ local technical personnel with high salaries, which may lead to the reverse spillover of technical knowledge to foreign-funded enterprises and reduce the technological innovation ability of local enterprises. It reduces the ability of local companies to develop clean technologies, which fail to improve the resource utilization efficiency of resource-based cities. 3) To gain competitive advantage and maintain a monopoly, foreign-funded enterprises are generally unwilling to transfer their core technologies (Chen et al., 2018a). Developed countries even transfer obsolete technologies to developing countries. Therefore, enterprises cannot obtain advanced clean technology through technology introduction, which cannot effectively improve the energy efficiency and the energy consumption structure of resource-based cities. Consequently, technology introduction is not conducive to the industrial green transformation of resource-based cities.

Third, technology introduction has increased the role of technological innovation in promoting the industrial green transformation of resource-based cities. Enterprises can digest and absorb technology introduced in resource-based cities, which would develop better performing products of higher quality, and obtain more market share than innovators and simple imitators (Shankar et al., 1998). In addition, increasing investment in scientific research and technological innovation can improve the imitative learning and technological innovation capabilities of resource-based urban enterprises. The improvement in enterprises' learning ability can effectively digest and absorb foreign-funded technology, enabling local enterprises to obtain advanced clean technology. This can improve the energy efficiency of resource-based cities and enable the green transformation of resource-based industries.

In addition, the heterogeneity test results show that the impact of technological innovation and technology introduction of different types of resource-based cities on industrial green transformation is different. Specifically, only the technology introduction of regeneration-type resource-based cities can significantly promote the industrial green efficiency of the region. Because regeneration-type resource-based cities have a more mature industrial structure and energy structure, they can effectively absorb the advanced clean technology introduced by technology introduction. Therefore, technology introduction can promote the industrial green transformation of regeneration-type resource-based cities. Simultaneously, for the interactions between technological innovation and technology introduction, technology introduction can effectively increase the impact of technological innovation on the green transformation of regeneration-type and maturity-type resource-based cities. This may be due to a relatively mature industrial structure and energy structure system of regeneration-type and maturity-type resource-based cities. They can continue to promote the green development of the industry by digesting, absorbing, and imitating foreign technologies. However, the coefficient before the interactions between technological innovation and technology introduction of recession-type resource-based cities is significantly negative, indicating that technology introduction will reduce the impact of technological innovation on green transformation. Because of the excessive development of resources and the relatively lagging industrial structure and energy structure in recession-type resource-based cities, local enterprises cannot improve production technology and energy efficiency by absorbing and imitating foreign technologies.

These conclusions have clear policy implications for choosing the path of technological progress in facilitating the industrial green transformation of resource-based cities in China. Simultaneously, the conclusions has certain reference significance for the sustainable development of resource-based cities in developing countries around the world.

First, technological innovation is an important strategic measure to improve the industrial green transformation of resource-based cities and achieve high-quality development. First, governments of developing countries should increase the funds and policy support for the green transformation of resource-based industries, while guiding and encouraging industrial enterprises to adopt green and clean technologies. At the same time, the government can use innovative governance models to promote the construction of a safe, efficient, clean, low-carbon, and green energy system. Second, by increasing investment in basic research, focusing on the self-accumulation of technological innovation knowledge, and seeking original technological innovation, it is possible to achieve competitiveness in the new international environment. Third, to improve the positive effect of technological innovation investment on the industrial green transformation of resource-based cities, the government also needs to improve the technological innovation system, introduce market mechanism, strengthen the protection of intellectual property rights, improve energy efficiency, and actively adjust the industrial structure. Furthermore, policies should encourage the research and development of clean and renewable energy technologies. In terms of energy structure, continuously increasing the proportion of new energy sources such as wind and solar energy and reducing the proportion of fossil fuel consumption will improve the level of green transformation of resource-based cities.

Second, policymakers of developing countries should continue to adhere to the strategy of introducing advanced technology using foreign capital. The technology spillover of foreign capital is an important factor in promoting the industrial green transformation of resource-based cities. China's resource-based cities should strive to improve the technology content of foreign investment, encourage developed countries in Europe and the United States, to invest, encourage foreign enterprises to use advanced technologies in China, and encourage foreign investment to undertake research and development activities. Simultaneously, the governments of resource-based cities should encourage enterprises to promote the introduction, assimilation, and re-innovation of innovation capability (Sun et al., 2012). Independent innovation and imitation innovation can not only improve the competitiveness of local enterprises but also encourage foreign enterprises to transfer technology. Furthermore, resource-based cities should introduce advanced clean energy technologies from abroad, improve the efficiency of clean energy utilization, optimize the industrial structure, and reduce dependence on high-carbon energy.

Finally, policymakers of developing countries should encourage enterprises to strengthen the digestion and absorption of introduced technology and lay a solid foundation for independent innovation, which reduces the technological gap with developed countries. Meanwhile, policymakers should encourage enterprises to integrate and imitate innovation, to accelerate technological innovation knowledge at a lower cost in a short period of time. Based on the introduction–digestion and absorption–imitation innovation, it is necessary to strengthen the ability of independent innovation and improve the level of independent innovation. Consequently, this will develop a new mode of introduction–digestion, absorption–imitation, and innovation-independent innovation. Finally, different policy support can be adopted for different types of resource-based cities. Resource-based cities should strengthen their ability to absorb technology, especially recession-type cities, which will improve low energy use efficiency in resource-based cities.

This study has room for further development and expansion. First, we mainly use a single index for the measurement of technological innovation and technology introduction. Therefore, to obtain more instructive research conclusions, we can consider expanding the indicator system and using more types of indicators. Second, we have analyzed resource-based cities with different attributes (i.e., coal and oil) into a unified framework. Future studies can consider collecting data on resource-based cities with different resource attributes for empirical research, thereby investigating the influencing factors of industrial green transformation of resource-based cities with different resource attributes.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. These data can be found here: China City Statistical Yearbook and Economy Prediction System (EPS) database.

AUTHOR CONTRIBUTIONS

WX performed drafting and writing, TY performed supervision and editing, SX performed supervision and editing, and FC performed editing.

FUNDING

This research was supported by MOE (Ministry of Education in China) Project of Humanities and Social Science (Project NO.17YJC790024).

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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.