Article

Can We be Optimistic about Carbon Neutrality Goal of China? A Research about The Mediating Role of Production Automation Based on Carbon Kuznets Curve

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Abstract: As China put forward its "carbon emissions peak and carbon neutrality" goals, how to achieve carbon reduction had become a key for China's goal. The manufacturing industry is an important source of carbon dioxide emissions. For a manufacturing country like China, adjustments in various aspects of the industry would have a huge impact on carbon emissions. As an important reform of contemporary production mode, the process of production automation in China will inevitably affect China's carbon emissions. Therefore, the analysis of the impact of production automation on carbon dioxide emissions was an important basis for judging the future carbon reduction in China. Refer to the traditional study of carbon Kuznets curve, this paper analyzed the impact of average wage on production automation and the role of production automation in the carbon Kuznets curve(CKC). This paper proposed that production automation plays a mediating role in the process of carbon emissions, and gives a verification model of the mediating role. By analyzing the relationship between average wage and production automation process, the U-shaped curve relationship between them was verified. By examining the relationship between carbon dioxide emission data and production automation industry in China, we verified that production automation plays a partial mediating role in the change of carbon Kuznets curve. Combined with the analysis of the two parts, this paper believed that with the continuous development of China's intelligent manufacturing industry, China's carbon reduction prospects were more optimistic, and there was a good industrial foundation to achieve the "carbon peaking and carbon neutrality" goals. Finally, this paper proposes policy suggestions as increase research investment in production automation, help promote the application of production automation, encourage the research and application development of low-carbon technology, especially encourage modular design, so as to give full play to the role of production automation in the process of carbon neutrality in China.

Keywords: carbon neutrality; production automation; mediating role; turning point; carbon Kuznets curve

1. Introduction

With the continuous development of China's economy, the scale of environmental costs of economic growth is increasing day by day. As the world's second largest economy and the world's largest real economy, how to control the environmental impact of development while ensuring economic development has become a problem that China must deal with at the present stage. In September 2020, Chinese President Xi Jinping, in seventy-fifth United Nations general assembly speech, announced that China will strive for carbon emissions peak by 2030 and become carbon neutral by 2060. It means that China will take overall low-carbon development as an important goal of the national development strategy in the medium and long term development plan.

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To achieve this goal, China has made corresponding planning arrangements for energy conservation and carbon reduction at different levels, including industrial development and social management. The goal of sustainable development requires development that meets the needs of the present without jeopardizing the ability of future generations to meet their needs. It can be seen that the key to ensuring sustainable development under the carbon peaking and carbon neutrality goals lies in how to effectively control regional carbon emissions, and the control of carbon emissions cannot be separated from the background of regional development. At present, China is in the stage of industrial development and transformation, and the intelligent manufacturing industry has become the key to China's industrial transformation, and in this process, the promotion of production automation is particularly obvious. At the aspect of labor force, the application of industrial robots has greatly changed China's manufacturing production mode, and the industrial automation represented by them will become a medium and long term trend of China's industrial development. Analyzing the impact of this trend on carbon emissions will help judge the development prospects of China's carbon emissions peak and carbon neutrality goals.

Therefore, the research focus of this paper is on the role of automation industry development in the process of carbon emission reduction in China. This study can help us to have better understand the role of production automation in the process of carbon reduction, and understand the path of carbon emission reduction. Based on this analysis, we can provide a basis for the prediction of the prospect on carbon neutrality goals, and it can also provides a new perspective on the construction of low-carbon development industry prospects for regions with similar goals and conditions. Structure arrangement is as follows, in Section 2, reviewed the relevant researches on carbon emission and production automation, and explained the basic viewpoints of this research; in Section 3, analyzed the relationship between automation and carbon reduction, and give the analysis framework of this paper; in Section 4, we establish an empirical model, and analyze the relationship between production automation and carbon emissions; in Section 5, discussed some conclusions of this paper and relevant research results; in Section 6, stated the main conclusions of this paper and give some policy recommendations.

2. Literature Review

For the analysis of carbon emissions, the most representative research is carried out around the carbon Kuznets curve (CKC). The theory of CKC originates from the hypothesis of the environmental Kuznets curve, and its basic point of view is: at the low income level, the regional environmental impact will increase with the increase of per capita output value; while at the high income level, it will decrease with the increase of per capita output value [1]. This hypothesis has been confirmed in many studies [2]. From the empirical analysis of different regions, the CKC hypothesis is generally applicable to explain the carbon emission process in different regions [3,4], which shows that this relationship also widely exists in the relationship between various human activities and carbon emissions [5]. What is certain is that the existence of CKC as a phenomenon has been recognized by most studies. Current research results mainly include three types of explanations for the causes of inflection points in the process of carbon emission change: institutional adjustment in the process of developmen [6], technological change that drives development [7], and the impact of related events [8]. In addition, there are explanations for the phased changes in the environmental impact of economic development from the perspective of civic awareness and other cultural aspects [9]. However, some scholars question the accuracy of carbon Kuznets curve from the perspective of model characteristics due to the ambiguity of detail description [10,11]. In order to supplement and improve the theory of CKC, Some scholars supplement the theory of carbon Kuznets curve by exploring the intermediary channels between economic growth and carbon emissions [12]. In general, to explain the relationship between socioeconomic development and carbon

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emissions, the carbon Kuznets curve is still applicable to explain the process of carbon emissions in most regions. At the same time, the extension model based on this theory has good extensibility. However, as pointed out by Webber and Allen, the phenomenon of environmental Kuznets curve generally exists in the process of changes of various environmental indicators, but the inflection points of changes caused by human activities on the environment are different in different cases [13]. Therefore, according to the development characteristics of different regions, the influencing factors of the change process of carbon emissions are analyzed from the key development characteristics. Such analyses are important for projecting regional carbon emission prospects.

For different regions, researchers have conducted a large number of analyses on their carbon emissions according to the important factors of regional development, and these analyses all show that the key development trends of the region have an important impact on regional carbon emissions. In the cases of developed countries or regions, by analyzing the impact of various socio-economic factors on carbon emissions in Central and Eastern Europe, Atici believes that per capita energy consumption in central and Eastern Europe is the main cause of local carbon emissions [14]. Vieira et al. analyzed the carbon emissions of European manufacturing and energy industries, and they pointed out that the main difficulty for EU countries to achieve the goal of net zero emissions lies in the emission control of large emitters [15]. Miura et al. analyzed the carbon emission contributions of economic sectors in different regions of Japan and pointed out that there are regional differences in the carbon emission contributions of different economic sectors, depicting the impact of carbon emissions in the modernization of Japanese industries [16]. These studies all show that the dominant factors of carbon emissions are different within the cases of the same developed countries. In contrast, the economic structure of developing countries is more diverse, and the factors for carbon emissions are more complex. For example, India's international tourism industry has grown rapidly in recent years, Jayasinghe and Selvanathan's study points out that international tourist spending is also an important factor in India's carbon emissions [17]. As a manufacturing power, China's carbon emissions have attracted extensive attention from scholars around the world. Jalil and Mahmud analyzed China's carbon emissions and pointed out that per capita income and energy consumption are the long-term determinants of China's carbon emissions [18]. Even within China, there are still differences in the carbon emissions of different regions. The study by Lu et al. points out that most of China's eight economic zones have already crossed the turning point of CKC and entered the ranks of low-carbon development, However, the northwest region still needs to be improved, and reason for this regional difference is China's differentiated regional development strategy [19]. Therefore, the analysis of the impact of China's key development trends on carbon emissions is of great significance for the analysis of China's carbon emission prospects.

At present, the world is in the stage of rapid development of emerging industrial technology, and at the production level, production automation is undoubtedly one of the most eye-catching trends [20]. Compared with the traditional production mode, the most significant advantage of production automation lies in its improvement of production efficiency [21,22], and at the same time, this process will bring about a reduction in the total share of labor added value [23]. In the early stage of production automation, its application is mainly for the automobile manufacturing industry, machinery manufacturing industry and other industries that are easier to promote fordism [24]. Obviously, there is a technical basis for promoting production automation in a wider range of fields, just like planting industry [25], breeding industry [26], and food production industry [27]. The increase of global risks represented by the global COVID-19 epidemic in recent years has become an opportunity for the further promotion of production automation technology [28,29]. These changes in production technology will undoubtedly have an impact on carbon emission reduction. Shin et al. 's study on the relationship between production automation and economic growth also shows that production automation contributes to the

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sustainable development of society [30]. Van and Morlet's study also points out that traditional environmental costs are gradually changing with the development of production automation [31]. As the world's largest manufacturing economy, production automation is an important trend of China's manufacturing transformation. Therefore, analyzing the impact of the development of production automation on carbon emissions is of great significance for judging the prospect of China's dual carbon strategy.

In order to analyze the details of the environmental external effects generated by a development trend, an important perspective is to start from the representative industry of this transformation. Focusing on the impact of key polluting industries [32] and the change of carbon emissions in industries with high energy consumption [33], or the change of carbon emissions in the process of service industry development [34,35], can reflect the impact of carbon emissions caused by industrial structural transformation; The research on the carbon emissions of the construction industry can reflect the details of the changes of carbon emissions in the process of urbanization [36,37]; The analysis of carbon emission changes in the transportation industry can be used to describe the changes in carbon emissions during the development of the trade circulation network [38,39]. In general, to analyze the environmental externality of a development trend, it is necessary to observe the environmental impact of the industry that can represent the trend.

Considering the research results of these literatures, we propose three basic understandings as follow: firstly, although there are differences in the understanding of the causes and development process, most studies agree that CKC exists as a phenomenon; secondly, on the basis of recognizing CKC as a universal law, most studies agree that the main development trend of a region greatly affects the local carbon emission process; thirdly, as an important form of modern manufacturing revolution, production automation is an important trend that will affect the development of China's future productivity.To sum up, the contribution of this paper is to add variables about production automation to the traditional CKC model, to analyze the impact of production automation on carbon emission changes, and provide a new viewpoint for the expectation of China's carbon emission reduction prospects.

3. Methodology and Data

To analyze the role of production automation in the process of carbon emission reduction, it is necessary to first clarify the relationship between the two. By reviewing the existing studies, we can confirm that there is a functional relationship between per capita income and carbon emissions in line with the CKC hypothesis [40], and per capita income has a strong impact on carbon emissions [41]. Previous studies usually associate it with changes in consumption level and consumption preference, and believe that changes in per capita income achieve carbon emission reduction through changes in consumer behavior [42]. However, when the research perspective is narrowed to the level of individual behavior, it may be difficult to explain the mechanism of CKC [43]. Therefore, from the perspective of income changes for future industrial development trends, this paper tries to put forward an analytical framework for the relationship between per capita income and total carbon emissions mediated by production automation, so as to discuss how the increase of per capita income affects total carbon emissions. The analytical framework is shown in Figure 1.

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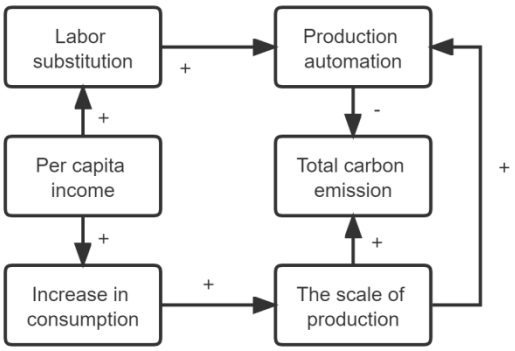

Figure 1. The role of production automation in carbon reduction

In this analysis framework, the effect of per capita income on carbon emissions is divided into two paths: (1) The increase of per capita income leads to the increase of total carbon emissions. The logic of this path is relatively simple, that is, an increase in per capita income will lead to an increase in personal consumption, which in turn will affect the production scale of consumer goods, and thus lead to the growth of carbon emissions; (2) The increase in per capita income will push up the labor cost in the production of products, and the increasing consumer demand will put forward new demands for improving production efficiency, thus promoting the development of production automation, which will promote the application of more carbon reduction technologies in the production process, thus helping to achieve carbon emission reduction. There are many related studies on the former path [44], so this path is not the focus of this paper. The second path is the key of this paper because it is able to explain the role played by production automation in the carbon reduction process, and can explain the cause of formation about CKC from the perspective of production mode reform.

Therefore, the problem to be demonstrated in this paper consists of two parts: firstly, whether the increase of income level can promote production automation; secondly, with production automation as the intermediary, how does the change of per capita income affect the total amount of carbon emissions. Since production automation contains more specific market behaviors, this paper will also observe the effects of different market developments on carbon emissions from different market behaviors.

3.1. How Does the Demand for Labor Substitution due to Rising Incomes Affect the Development of Production Automation

In the analytical framework proposed in this paper, the first relationship to be tested is whether the increase in per capita income will lead to the development of production automation. In this analysis framework, the impact of per capita income on the production automation industry has two paths: (1) the increase of per capita income will become the labor cost in the production process, which will stimulate the demand of manufacturing enterprises for labor substitution in the production process, and then promote the development of the production automation industry [45]; (2) The increase of per capita income can stimulate the consumption willingness of residents, resulting in the increase of market consumption demand, and then expand the production scale of consumer goods [23]. These theories are based on studies in regions with more developed productivity. When we look at the longer term of development, this unilateral promotion may have its limits. We attempts to take a longer view of the impact of increasing income on the development of production automation.

Production automation is essentially a reform of the production mode of manufacturing industry. In this trend, the influence of wage income (the price of labor) on the

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process of production automation is different at different stages. The basis of this judgment is as follows: firstly, the scale of production is proportional to wage income. The larger the scale of production, the higher the wage income [46]; secondly, according to the theory of marginal effect of scale, there is an intersection between marginal revenue and wage income. On the basis of these two conclusions, we can see that with the expansion of the scale of production (with the rise of the price of labor), the process of the change can be depicted in Figure 2. In the diagram we can see two important points, the first is the apex of the marginal benefits of scale (X_1), and the second is the intersection of labor costs and marginal benefits (X_2). These points, especially X_2, can be helpful to understand the relationship between labor price and production automation. The impact of labor price on production automation is manifested in two directions, which can be regarded as the characteristics of two development stages: In the early stage of large-scale development, the price of labor is relatively low, and the boundary effect generated by the expansion of production scale makes it profitable for enterprises to expand production by increasing labor, so there will not be a strong demand for the realization of production automation at this stage (in the left range of X_2). With the increase of labor price, the scale effect of expanding production will be gradually exceeded by the increase of labor cost. In contrast, production automation becomes one of the options for cost control, so there will be an increasing demand for production automation .(in the right range of X_2)

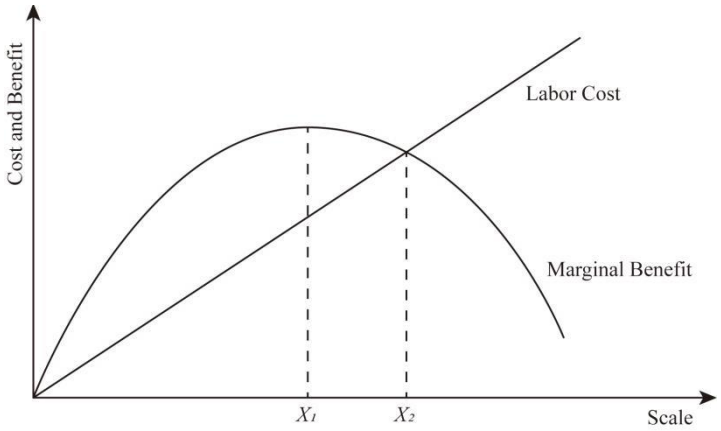

Figure 2. Labor cost and marginal benefit in the process of scale expansion

To sum up the above analysis, we can make a basic inference: at the stage of low labor price, with the increase of labor price, the demand for production automation will decrease; at the stage of high labor price, the demand for production automation will increase with the increase of labor price. Therefore, in terms of function form, there should be a U-shaped curve between labor price and the development of production automation. In order to verify this relationship, this study uses a static panel model for preliminary test.

$$PA = \beta_1 \cdot GDP + \beta_2 \cdot EC + \beta_3 \cdot AveWage + \sum \beta_i \cdot X + \gamma \quad (1)$$

$$PA = \beta_1 \cdot GDP + \beta_2 \cdot EC + \beta_3 \cdot AveWage + \beta_4 \cdot AveWage^2 + \sum \beta_i \cdot X + \gamma \quad (2)$$

Where, PA represents the development of production automation, and the explanatory variables are GDP, EC and $AveWage$, which respectively represent the regional gross product, the total regional energy consumption and the average salary of employees. X is the control variable, including population urbanization rate, total bank loans, manufacturing output value and population education level. By comparing the results of the two equations, we can test the relationship between the number of market players in the industrial robot industry and the average wage level. If both β_3 and β_4 of equation (2) are

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significant, and the goodness of fit of Equation (2) is better than that of equation (1), then the relationship between labor price and production automation can be considered as a U-shaped curve. The turning point of the curve can be regarded as the position of X_2 in Figure 2. When the per capita income come to the right range of turning point, the increase in per capita income will promote the progress of production automation.In other words, the need for automation due to the increase in per capita income does not occur until the turning point is crossed.

Base on this model, we can further observe the details of the impact of economic development on production automation. Because of the highly detailed division of labor in the production automation industry, enterprises engaged in related work may be affected differently by changes in per capita income according to their own work in the industrial chain. From the perspective of the process of industrial demand, the market activities related to production automation can be divided into the research on production automation, manufacturing of equipment, and all kinds of services related, such as promotion, marketing, after-sales, maintenance, etc. These demands should occur in a sequential order: before the actual application, there will be a demand for research and development of related technology, and only after that, there will be a demand for manufacturing and other services. In the early stages of development, Since the technology was not yet perfect, and the market demand is still relatively small, the manufacturing enterprises of relevant equipment both need and have the ability to provide the services, such as marketing, maintenance, installation. And when the wage further increases, the market demand expands, it will produce the demand of specialized service. This inference can be expressed in the form shown in Figure 3.

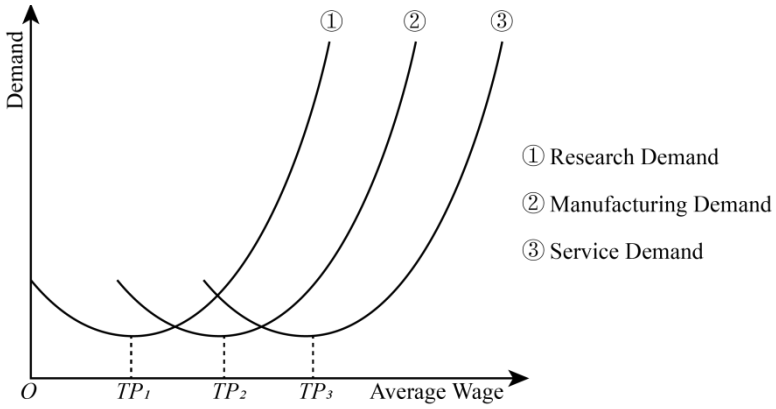

Figure 3. The turning point of different demand

Continuing the prediction, it can be believed that with the increase of average wages, the demand for production automation will continually increase, and the process of production automation will persistently accelerate. This prediction can be verified by the inflection point of Equation (4). The demand for production automation can be divided into research and development, manufacturing, and service, which are respectively substituted into Equation (4) for testing, and the difference of their turning points can be analyzed. Thus, the demand generated in different stages can be verified.

3.2. The Mediating Role of Production Automation in Carbon Reduction

In the analytical framework of this paper, another relationship that needs to be verified is the mediating role of production automation in carbon emission reduction. The reasons to believe that production automation as contributing to carbon emissions, the direct one is that the essence of production automation is to further standardize the production process, and cutting more randomness from subjective judgment in human labor

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working. Production automation has the characteristics of modular, so that technical updates to be integrated into the production module, and be easier to be applied to the production process. Another context is that China's energy structure has changed significantly over the past twenty years. As a production mode that relies on electricity as the main energy, automated production means an increase in electricity energy consumption. From 2000 to 2018, China's energy structure changed significantly. Among them, the share of coal energy decreased from 68.5% to 59.0%, and that of petroleum energy decreased from 22.0% to 18.9%, which are major sources of carbon emissions. In contrast, in terms of clean energy, share of natural gas increased from 2.2% to 8.4%, and that of other clean electricity increased from 7.3% to 14.5%. In the context of this changing of energy structure, we can sure that production automation means that more consumer goods are produced by using cleaner energy.

By the analysis, we can make a basic inference that production automation plays a partial mediating role in the process of carbon emission reduction, that is, production automation is a means to assist the realization of carbon emission reduction. Before building the model, we first need to select the variables to be modeled. First of all, the core issue to be explained in this study is the role of production automation in CKC phenomenon, so it contains the variable PA that represents production automation, It also needs to include AveWage, a core explanatory variable representing labor prices [47]. In addition, the impact of production scale on carbon emissions has been confirmed in a large number of empirical studies [48], and energy consumption is a more direct factor affecting carbon emissions [49], so both are included as explanatory variables. The above four variables are explanatory variables of this study, in order to eliminate the influence from other factors, some common influencing factors in CKC related research, Select four control variables [2,50-52]. To verify this inference, refer to the research on mediating role [53], we designed Equations (3) and (4) to verify the partial mediating role:

$$CE = \beta_1 \cdot GDP + \beta_2 \cdot EC + \beta_3 \cdot AveWage + \beta_4 \cdot AveWage^2 + \sum \beta_i \cdot X + \gamma \quad (3)$$

$$CE = \beta_1 \cdot GDP + \beta_2 \cdot EC + \beta_3 \cdot AveWage + \beta_4 \cdot AveWage^2 + \beta_5 \cdot PA + \sum \beta_i \cdot X + \gamma \quad (4)$$

Where, *CE* is the regional carbon emissions, and the explanatory variables are *GDP*, *EC*, *AveWage*, and *PA*, which respectively represent regional gross product, energy consumption, average wage, and production automation. *X* is the control variable, including population urbanization rate, total bank loans, manufacturing output value and population education level. By comparing the difference between the correlation coefficient in Equation (3) and Equation (4), we can verify the role of production automation in the process of carbon emission reduction. According to our analysis, if β_3 and β_4 are significant in Equation (3), it indicates that the phenomenon hypothesized by CKC exists, there is a turning point in China's carbon emissions, when the average wage higher than the turning point, carbon emissions will reach a peak and start to decline gradually as the average wage increases; And in Equation (4), if β_3 and β_4 are still significant, and β_5 is also significant, it indicates that production automation is one of the pathways in CKC hypothesis processes to reduce carbon emission, and it has partial mediating role.

3.3. Data

According to the validation model built by the above analysis, we selected 9 variables for analysis. The research time range was from 2000 to 2019, and the research sample were 289 cities with districts in China. The description of each variable was shown in Table 1.

Table 1. Variable descriptions

Variable		Symbol
Explained variable	regional carbon emissions	CE

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Key variable	production automation	PA
Core explanatory variable	average wage	AveWage
Other explanatory variables	regional gross product	GDP
	energy consumption	EC
Control variables	population urbanization rate	UP
	Financial sector activity	FA
	manufacturing output value	MO
	population education level	PE

(1) Regional carbon emissions. This paper chose The Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC) Fossil Fuel Emission Dataset (ODIAC2020b) as an indicator of regional carbon emissions, this dataset draws a 1x1km distribution image of global fossil fuel carbon dioxide emissions through emission modeling methods [54]. The impact at this resolution can effectively reflect the carbon dioxide emissions at the spatial scale of prefecture-level cities. Using the carbon emission raster data of ODIAC superimposed on the administrative boundaries of prefecture-level cities, the carbon emissions of 289 sample cities from 2000 to 2019 can be extracted.

(2) Production automation. For the observation of production automation, this paper chooses the perspective of enterprises engaged in production automation related market activities, and took the number of relevant enterprises in the region as the index. The number of enterprises engaged in an industry can reflect the market demand for the industry, so the number of relevant enterprises engaged in providing production automation services in a region can well reflect the development of production automation in the region. Through the online data platform of Qcc.com (https://www.qcc.com/), the national industrial and commercial registration data is retrieved according to the standard that the business scope includes the business content related to production automation. The industrial and commercial registration data was used as the basis for judging the existence of enterprises to determine the number of production automation enterprises in different years and different regions. After filtering, there were 77,484 enterprises in 289 sample areas. Then the number of enterprises engaged in production automation related work in each region from 2000 to 2019 is obtained. According to the different types of enterprises engaged in production automation service work, the research enterprises, production enterprises and service enterprises were classified, denoted by PA_R, PA_M and PA_S respectively..

(3) The explanatory variables. The core explanatory variables of this article was urban worker average wage, the reason the town worker's average wage rather than the manufacturing worker's average wage is that due to the lack of obvious industry barriers in modern labor force, the flow of labor force between industries is more and more frequent. Therefore, the average wage of urban workers, which can reflect the overall level of labor income, could better reflect the impact of wage changes on production automation. Other explanatory variables also included regional gross product and energy consumption, reflecting the impact of regional economic size and energy use, respectively. These datas acquired from EPS data platform (https://www.epsnet.com.cn).

(4) Control variables. The control variables selected in this paper include population urbanization rate, financial industry activity, manufacturing output value and population education level. The urbanization rate of population was expressed by the population with urban household registration divided by the total population of the region. Financial industry activity is represented by total social loans. The education level of the population was represented by the proportion of the population with college education or above in the total population in the sample population survey of the concept area.

4. Results

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4.1 Unit Root Test

In order to avoid errors in regression results caused by data problems, unit root tests were conducted on all variables. If there was a unit root, the panel data was unstable. It is necessary to differential the data. After the first-order difference processing, all variables pass the unit root test, and the results of the unit root test were shown in Table 2. Therefore, all variables in this study were first-order single-integer sequences.

Table 2. Results of unit root test after first difference

	Units	Levin, Lin&Chut*	Im, Pesaran and Shin W-stat	ADF-Fisher Chi-square	PP-Fisher Chi-square
CE	million tons	0.0000	0.2228	0.0000	0.0000
PA	num	0.0000	0.0000	0.0000	0.0000
AveWage	ten thousand CNY	0.0000	0.0000	0.0000	0.0000
GDP	million CNY	0.0000	0.0000	0.0000	0.0000
EC	tons of standard coal	0.0000	0.0000	0.0000	0.0000
UP	%	0.0000	0.0000	0.0000	0.0000
FA	million CNY	0.0000	0.0000	0.0000	0.0000
MO	million CNY	0.0000	0.0000	0.0000	0.0000
PE	%	0.0000	0.0000	0.0000	0.0000

4.2. Verification of the Relationship between Average Wage and Production Automation

Base on Equations (1) and (2), the relationship between average wage and production automation was verified. The Hausman test was first used to select the type of model effect, and the test results were shown in Table 3. The test results show that the chi-square value was 341.63 and Prob was less than 0.05, so the fixed effect model was selected. The regression results were shown in Table 4.

Table 3. Hausman test results

Test Summary	Chi-Sq. Statistic	Prob.
Cross-section random	341.633713	0.0000

Table 4. Fixed effects regression results.

	Coefficient	
Variable	(1)	(2)
AveWage	0.3554***	-2.1465***
AveWage^2	—	0.1539***
GDP	0.4869***	-0.0604
EC	1.2268***	1.4278***
UP	-3.1834***	-2.6002***
FA	-0.0231***	-0.0158***
MO	0.4480***	0.4419***
PE	1.5358***	1.0871***
C	-9.5880***	0.9070***
R-squared	0.9005	0.9070
Adjusted R-squared	0.8949	0.9017

Note: *** represent significant at the 1% levels.

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It could be seen from the results expressed that, the goodness of fit in Equation (2) was better than that of Equation (1), indicating that the regional average wage income level and the number of industrial robot enterprises present a quadratic function relationship, and the correlation coefficient shows that the relationship between the two was a U-shaped curve. Therefore, the following analysis was based on the regression results of Equation (2). The results of core explanatory variables show that the relationship between regional average wage income and industrial robot enterprises is significant, which verfies the previous conjecture in this paper that there is a U-shaped function relationship between per capita wage income and production automation. According to the coefficient, the turning point of the relationship between per capita wage income and production automation is 6.9748 (X_2), indicating that when the regional average income level is lower than CNY 69,748, the scale effect of labor agglomeration caused by wage growth is greater than the increase of labor cost caused by wage growth, and the increase of wage level will inhibit the demand for robot substitution in regional industries. When the average income level is higher than CNY 69,748, the increase of labor cost exceeds the marginal productivity. In terms of other explanatory variables, in Equation (2), the relationship between regional economic scale and production automation is not significant, while the relationship between energy consumption and production automation is significant.

According to the analysis in 3.2, replacing *PA* with the number of different types of production automation enterprises into Equation (2), to verify the sequence in which the different need for production automation arises. In Table 5, PA_R on behalf of research enterprises, PA_M on behalf of manufacturing enterprises, PA_Son behalf of service enterprises. The test results are shown in Table 5.

Table 5. Fixed effects regression resultsof different types of enterprises.

	Coefficient		
Variable	**PA_R**	**PA_M**	**PA_S**
AveWage	-1.8435***	-2.0829***	-2.0313***
AveWage^2	0.1468***	0.1482***	0.1423***
GDP	-0.0503	-0.0578	-0.0596**
EC	1.3281***	1.2307***	1.3451***
UP	-2.3800***	-2.5978***	-2.4861***
FA	-0.0155***	-0.0154***	-0.0145***
MO	0.4020***	0.4229***	0.4217***
PE	1.0228***	0.9220***	1.0117***
C	5.4727***	5.3819***	5.8273***
R-squared	0.8760	0.8795	0.8654
Adjusted***R-squared	0.8052	0.8700	0.8432

Note: **, and *** respectively represent significant differences at the 5%, and 1% levels.

From the perspective of different types of enterprises, in terms of core explanatory variables, there is a positive U-shaped relationship between the average wage level and the three types of production automation enterprises. Among them, the inflection point of research enterprises is 6.2789, that of production enterprises is 7.0252, and that of service enterprises is 7.1373. It verifies that in different stages of development, the demand for production automation will change differently. This will be elaborated in the discussion section of this paper. In terms of other explanatory variables, the GDP is only significant in the model of service-oriented enterprises, indicating that the regional economic scale is conducive to the development of service-oriented enterprises. Regional energy consumption has a significant positive impact on the three types of enterprises, with the largest impact on production enterprises and the smallest impact on research enterprises.

4.3. Verification of the mediating role of production automation

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Base on Equations (3) and (4), the mediating role of production automation in the carbon emission process was verified. The Hausman test was used to select the model, and the test results show that the chi-square value of Equation (3) is 111.22 and Prob was less than 0.05, and the chi-square value of Equation (4) is 116.82 and Prob was less than 0.05. Therefore, fixed effects were used in both models. The regression results were shown in Table 6.

Table 6. Verification of the mediating effect of production automation

	Coefficient	
Variable	**(3)**	**(4)**
AveWage	0.2379***	0.2042***
AveWage^2	-0.0113***	-0.0089***
PA	—	-0.0157***
GDP	0.4853***	0.4844***
EC	-0.0896***	-0.0672**
UP	0.0626	0.0218
FA	0.0049***	0.0046***
MO	-0.0528***	-0.0458***
PE	-0.0762***	-0.0591***
C	6.9468***	7.0464***
R-squared	0.9832	0.9832
Adjusted R-squared	0.9822	0.9823

Note: **, and *** respectively represent significant differences at the 5%, and 1% levels.

Judging from the test results, firstly, the correlation coefficient of the average wage in Equations (3) and (4) showed that there was an inverted U-shaped curve between the regional average wage and regional carbon emissions, which also verfies the existence of the CKC curve [55]. That means, with the increase of wage income, more and more regions will enter the stage of carbon emission reduction. Secondly, before and after the production automation index was added, the correlation coefficient between average wage and carbon emissions was significant, and the correlation coefficient of production automation in Equation (4) was also significant, indicating that production automation has a partial mediating effect in the process of carbon emission reduction. The correlation coefficient of production automation in Equation (4) was negative, indicating that production automation played a role in inhibiting carbon emissions in the process of regional carbon emissions change. This also verified the conjectures made during the model construction phase.

5. Discussion

Some speculations in the third part of this paper have been verified by empirical tests. The relationship between the results of this paper and some related studies was further discussed below.

5.1. The Development Prospect of Production Automation

Production automation, as a revolution in production technology that has been underway for decades, has already surpassed the technical limitations of its initial development. From the initial application scenarios that can only be applied to some standardized assembly lines, such as automobile industry, to today has gradually entered a more extensive production process, production automation will undoubtedly greatly change the future manufacturing production mode [56]. Most of the previous studies on production automation focus on the external effects of production automation, regard it as the technological factors that drive other changes in the economy, and to a large extent regard

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production automation as a simple technological innovation, while there are few discussions on the economic laws of the development of production automation. From our analysis in this paper, it can be basically determined that with the increase of average wage, labor cost will promote the further popularization of production automation.

From the turnin points of per capita wage for different types of enterprises, we can find that the demand for production automation did not come naturally from the beginning, but gradually occur at different stages. As wages rising, the demand to know the technology of production automate occur first, creating a need for research firms. Like other production changes in history, this was a technological preparation for a new production change. What follows is the demand for the production of related equipment, that is, in some regions with the highest level of wage income, the demand for the use of automation equipment is generated. Firms in these regions are the first to get the pressure from rising wages and therefore they are first to have demand to use automate production for replacing human labor. At this stage, production automation has begun to develop in a few developed areas, and then entered the field of scenario application. This can be mutually proved with the development history of production automation [57]. With the continued development of economy, average wages in most areas are higher than the turning point, and the demand of production automation will occur in these regions. Comparing the average wages of sample cities in 2019, 203 of the 289 sample cities have crossed the last inflection point and entered the stage of widespread popularization of production automation. It can be expected that with the further innovation of production automation technology, the application scenarios of production automation will be more extensive, and the research on the impact of production automation on various aspects will be more realistic.

In addition, the conclusion in this paper about the sequence of the turning point of different demands on production automation can also shows that the first-move regions will generate the demand for production automation earlier, and lead the framework of the industry related to production automation. This phenomenon is reflected that, despite the demand for production automation are arising in most regions and related enterprises covering most of the sample cities, but firms engaged in research and manufacturing are still concentrated in a few large urban agglomeration centers.

5.2. the effect of production automation on regional carbon emission

The environmental impact of production automation has also been discussed in relevant studies [58,59]. In general, the most prominent significance of production automation for the environment is that it can further reduce the randomness in the traditionally human-dominated process and further standardize the whole production process. At the same time, in the application of production automation, standardized and modular production mode is more conducive to the application of new energy-saving technology. Compared with human labor, that new technologies and standards need to be trained for staff, it can be directly nested into existing modules in the production process of production automation, which is obviously more conducive to the promotion and application of environment-friendly technologies. Just as the results verified in this paper, production automation plays a partial mediating role in the process of carbon emission, that is to say, production automation itself is only one of the paths in the process of carbon emission reduction. To make production automation works, it still needs research and development of environmental technologies at the source. In the case of the development of environmental protection technology, production automation can help accelerate the process of technology application, thus playing a positive role in carbon emission reduction.

From this perspective, we can predict that in the future, the application of production automation will be more widely used. As the world's largest industrialized country, the process of production automation in China will also greatly change the production mode of China, and more and more production scenarios will apply the related technologies of

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production automation. This also means that under the background of vigorously promoting environmental protection technology innovation, relevant technologies will be more convenient to be applied in the production process, helping China to achieve the strategic goal of "carbon emission peak and carbon neutrality". We can be optimistic about China's prospects for carbon neutrality.

6. Conclusions

This paper attempts to discuss the role of production automation in the process of carbon reduction under the framework of CKC theory based on the economic characteristics of production automation and the observation point of relevant market activities. Based on the panel data of 289 sample cities in China from 2000 to 2019, this paper analyzes the development law of production automation and its significance for carbon emission reduction. The main findings of this paper are as follows:

(1) The relationship between average wage and production automation shows a U-shaped curve, indicating that in the early stage of economic development, the marginal cost of expanding production is low, so the increase of wage does not promote the demand for production automation; When average wage higher than the turning point, the increase of wage will promote the development of production automation.

(2) The influence of average wage are different in various types of production automation, while the whole results show as the form of a u-shaped curve, but the three types of production automated enterprise have different turning point, reflecting the average wage change in the process, the demand of production automation occur sequentially. The industry will first begin to prepare the technology to automate production, and then create specialized research units; Then, it starts to develop equipment manufacturing enterprises in a few pioneer areas, and finally spreads to more regions through related service enterprises.

(3) From the verification results of the mediating effect, production automation plays a partial mediating role in the process of carbon emission reduction. It indicates that production automation is an intermediate medium that can promote carbon emission reduction. The promotion of production automation will help achieve China's goal of "carbon neutrality".

With the conclusions, this paper has a relatively optimistic expectation for the realization of China's strategic goal of "carbon peak and carbon neutrality." China's development will enable production automation to be more widely used in various economic scenarios, and the promotion of production automation also makes it easier to apply various low-carbon technologies in the production process. At the same time, based on the findings of this paper, two suggestions are put forward to promote carbon emission reduction:

(1) Increase research investment in production automation, promote the application of production automation. Nowadays, most regions of China have the economic conditions of the process of production automation, relevant development plans for production automation and intelligent development have also been formulated. In further stage, the government needs to strengthen the supervision and guidance of production automation related industries, to ensure the stability of automation market development while promoting related technologies, and specify the development direction of production automation. At the same time, the government also needs to encourage production enterprises to use production automation technology by fiscal and tax subsidies and other financial tools, to accelerate the promotion of production automation, and prepare the industry base for the application of low-carbon technology.

(2) Encourage research and application of low-carbon technologies, especially modular design. The conclusion of this paper shows that the production automation is one of path to promote carbon reduction, and carbon emissions in essence still need low carbon technology innovation and promotion, production automation of play is to improve the new technology to promote the role of the environment. So it will still need to encourage

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low-carbon technology innovation, and for the application of low-carbon technologies into the production automation provides favorable market conditions. In particular, encourage the development of modular designs that can be directly applied to automated production processes, to make low-carbon technology can be more convenient to apply in production link.

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