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Analysis of low-carbon technology innovation efficiency and its influencing factors based on triple helix theory: Evidence from new energy enterprises in China

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A R T I C L E I N F O

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Panel tobit model

A B S T R A C T

Background and aim: Low-carbon technology innovation(L-CTI) is an essential way to realize the socio-economic transition to a low-carbon model. However, relatively few studies have been conducted on the calculation of low-carbon technology innovation efficiency(L-CTIE) and the identification of factors influencing it. The study intends to assess the L-CTIE of new energy enterprises(L-CTI-NEEs) and to analyze its influencing factors, so as to further improve the L-CTIE capability.
Methods: Using the panel data of new energy enterprises(NEEs) in 2010-2020, DEA(BCC)-Malmquist-Tobit method is constructed to static and dynamic evaluate the L-CTIE of new energy enterprises(L-CTIE-NEEs), and analyze its influencing factors with triple helix theory.
Results: During the study period, the L-CTIE among NEEs was quite different, and the Malmquist index change trend had phased characteristics. From the perspective of factors influencing innovation efficiency, technology integration capacity of enterprises, support intensity of government and cooperation scale of government-enterprises-universities & research institutions play a crucial part in promoting the EEFCH, PECH and SECH of L-CTIE-NEEs, while resource conversion capacity of universities & research institutions only promotes PECH.
Conclusion: According to the research results, a triple helix model of L-CTI-NEEs is constructed to enhance its L-CTIE level.

1. Introduction

As a model of economic development that is low in emissions, energy, and pollution [1], low-carbon economy is a basic approach of addressing conflicts between environmental systems, resource, and population in human social development [2]. It is a decision that all nations in the world have made in favor of sustainable development [3]. Most scientists concur that advancing and implementing low-carbon technologies is a key strategy for lowering emissions [4]. Low-carbon technology innovation(L-CTI) can bring breakthroughs and improve resource utilization efficiency. It is key to achieving a low-carbon economy and can create a win-win scenario for economic and social development as well as environmental protection. But it is difficult for enterprises to control and predict the

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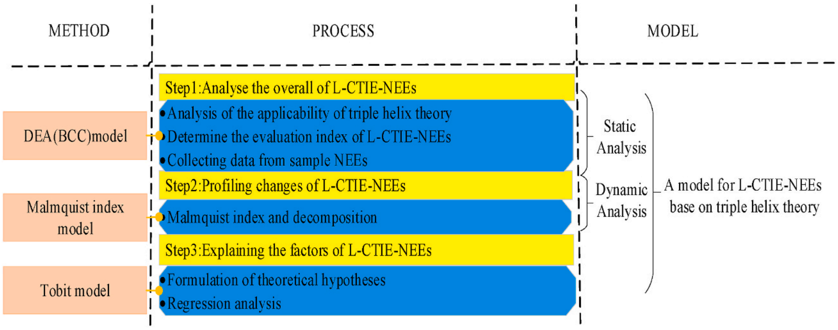

Fig. 1. Stream outline of research process.

risks of high technology investment costs and the difficulty of promoting the results in the process of L-CTI, which hinders the development space of L-CTI [5]. Finding strategies to enhance L-CTI and L-CTIE, translate low-carbon technology into direct productivity, and effectively support the development of a low-carbon economy have therefore become crucial issues for businesses and society as a whole. Chinese government adopted several policies. These include the need to accelerate technological progress in energy conservation, promote innovative new technologies, equipment and techniques for energy conservation, encourage economical and intensive use of energy resources [6]. Low-carbon technology innovation efficiency(L-CTIE) is the efficiency with which transforming innovation input into output in L-CTI activities. From a long-term development perspective, L-CTIE levels reflect enterprises' low-carbon technology levels and future development trends, which directly affect their sustainable development capability and competitiveness. Therefore, in order to realize the low-carbon mode of Chinese economic development as soon as possible, it is of great significance to scientifically measure the L-CTIE of enterprises and explore their key influencing factors to further enhance their L-CTI capability.

In the last few years, scholars have researched L-CTI extensively, involving a variety of perspectives, disciplines and subjects. On this basis, scholars have also conducted further research on the L-CTIE. In terms of research content, it mainly focuses on a certain level such as country(or region or city), industry and enterprise, with new energy vehicles being the majority. In terms of research content, it mainly focuses on certain levels such as countries(or regions, cities), industries, and enterprises. At the national level, it is mainly reflected in the role of policies [1], at the industry level, it is mainly the exchange of technological innovation between enterprises [2], and at the enterprise level, it is mainly focused on new energy vehicles [6]. From a research perspective, there is more static analysis of differences between regions or industries, as well as between enterprises, than dynamic analysis [4]. Regarding research methods, DEA is the principal approach, but some studies have also chosen the Durbin model.

Hence, this study depends on triple helix theory and observes the internal laws of saving energy, reducing emissions and developing a low-carbon economy from government, enterprises and universities & research institutions, measuring and providing decision guidance. As regards research methods, a DEA(BCC)-Malmquist-Tobit method was constructed. The method conducts static and dynamic measurements of the L-CTIE-NEEs, and further analyzes its influencing factors. This provides directions and strategies for improving the quality and benefits of low-carbon technology, effectively helps enterprises to form differentiated competitive advantages, and rapidly develops the low-carbon market [6]. This is shown in Fig. 1.

2. Theoretical analysis

2.1. Analysis of the applicability of triple helix theory

Triple helix theory explains interdependence between universities, enterprises and government in social and economic development. It means that under the role of economic development needs, universities, enterprises and government, on the basis of structural arrangements and institutional design and other mechanisms, influence and link with each other for the purpose of maximum sharing of resources and full communication of information among the three [7]. Triple helix theory has been extensively studied in technological innovation. In accordance with triple helix theory, Fu et al.(2015) used case analysis and empirical models to break down the impact of universities, enterprises and government on technology innovation in terms of technology transfer [8]. Li and Yu(2014) and Scalia et al.(2018) both analyzed empirically and studied government's driving role in firm technology innovation from triple helix theory perspective [9,10]. Lin et al.(2017) created a framework for interpreting triple helix theory of high-speed rail and explained the interaction mechanism among the innovation subjects in the complex system of high-speed rail technological innovation [11]. Wei and Li(2020) applied evolutionary game theory to analyze each innovator's function in a triple helix, and the law of cooperation among the three in industry common technology innovation [12]. Zhuang et al.(2021) planned a regional cooperative development assessment model in view of triple helix theory to examine the connection and coupling of industries, universities and governments within and between regions [13]. By establishing triple helix collaborative innovation model, the scientific research and technical service industries, which are clusters of innovating subjects in the region, increase the degree of influence and significance of the collaborative innovation effect [14].

According to triple helix theory, this study defines low-carbon technology innovation of new energy enterprises(L-CTI-NEEs) as a process in which government, enterprises and universities & research institutions work together to open up the original technological and economic system through a technological paradigm shift. Low-carbon technology innovation efficiency of new energy enterprises (L-CTIE-NEEs) refers to the extent to which the synergistic model formed by the effective interaction among the government, enterprises and universities & research institutions contributes to the output of L-CTI. With the L-CTI process, three innovation subjects of government, enterprises and universities & research institutions correspond to three spirals. They interact with each other, influence each other and spiral upwards, thereby promoting the continuous rise of the innovation spiral [15]. In the process of interaction, there is not only bilateral cooperation, but also trilateral hybrid cooperation. Three spirals of innovation subjects simultaneously play a supporting role in their own category and other spiral categories. For instance, universities & research institutions and enterprises cooperate to incubate their own achievements, government supports enterprises development and technical research in universities & research institutions through project funding and other forms, and enterprises provide positions for universities & research institutions talents to ensure their own sustainable development.

2.2. Theoretical hypotheses

There are fewer relevant studies assess L-CTIE-NEEs and to analyze factors influencing it, so further justification is needed. Therefore, continuing the existing research idea, with the help of relevant studies on L-CTI, further analysis of L-CTIE. Considering the characteristics of NEEs with large asset investments and long return cycles. Based on triple helix theory, close cooperation and multi-dimensional collaboration among government, enterprises and universities & research institutions can form a synergy to promote the L-CTI, achieve the continuous evolution and upgrading of their L-CTI systems, improve the L-CTIE. According to the research purpose, from the perspective of innovative subjects, researchers screened and organized relevant literature, as shown below (see Table 1).

Table 1
Literature collation.

Innovation Subjects	Opinions	Authors
Government	government low-carbon policies	Castillo & Linn [16] Wu et al. [17] Chen et al. [18]
	government low-carbon regulation	Bi et al. [19] Jänicke & Lindemann [20]
	government low-carbon encouragement	Feng et al. [21] Baker et al. [22] Sovacool [23]
	government low-carbon innovation subsidies	Zhang et al. [24] Dou & Cui [25] Wiadek et al. [26] Li et al. [27]
	carbon tax	Wang et al. [28] Chen et al. [29] Deng et al. [30] Chen et al. [31]
	carbon emission trading systems	Eichner & Pethig [32] Narayan & Sharma [33] Calel & Antoine [34] Teixido et al. [35] Lyu et al. [36]
Enterprises	L-CTI(including willingness, cost, returns and application)	Xu & Qu [37] Fu & Cai [38] Przychodzen [39] Weber & Neuhoff [40]
	low-carbon policies incentives	Zhang et al. [41] Wang & Zheng [42]
	low-carbon policy intervention	Shi et al. [43] Zhai et al. [44]
	market demand	Olmos et al. [45] Costantini et al. [46]
Universities & research institutions	low carbon technology innovation system	Hendry et al. [47] Kennedy & Basu [48] Gosens et al. [49]
	basic and critical low carbon technologies market demand	Ou & Zhang [50] Olmos et al. [45] Costantini et al. [46]
Any two innovation subjects	Including common collaboration, strategy selection strategy choice etc.	Sheu & Chen [51] Kennedy & Basu [52] Yang et al. [53] Xu et al. [54] Liang & Fu [55] Wang & Li [56] Shang et al. [57]

Through the review of the above literature, it has been found that government, enterprises and universities & research institutions are both providers of innovation elements and direct innovation subjects. Not only do they play their roles in bilateral cooperation, but the boundaries between the three are fluid. This ensures the barrier-free flow of information, talents and other resources, and gives full play to the function of promoting L-CTI. Therefore, this study selects technology integration capacity of enterprises, resource conversion capacity of universities & research institutions, support intensity of government, and cooperation scale of government-enterprises-universities & research institutions as the influencing factors of L-CTI-NEEs, and the following theoretical hypotheses were obtained:

Relying on internal resources and external resources provided by the government and universities & research institutions, NEEs have created a technological innovation system with their own characteristics. They are the main subjects of L-CTI. The level of technology integration capacity of enterprises refers to the identification and acquisition of resources provided by government and universities & research institutions by the enterprise, and the combination and application of the resources provided by the enterprise to improve the level of L-CTI. NEEs rely on contracts and economic benefits to form a multi-faceted cooperation situation with government and universities & research institutions in terms of talents, technology, management, etc., which greatly promotes low-carbon technology breakthroughs and results, and is conducive to improving low-carbon technology for enterprises innovation efficiency [58]. Sun et al. (2022) analyzed the positive effect of economy and technology inputs on L-CTI growth [59]. A enterprise's ability to innovate in green technology has a remarkable positive effect on its competitiveness, and the impact on competitiveness varies depending on the components of the ability to innovate in green technology [60]. Hence, NEEs internalize the knowledge flow, technology flow, talent flow, capital flow and culture flow received from the government and universities & research institutions into their own L-CTI resources and improve the L-CTI system, which is beneficial to improve the L-CTIE of enterprises. Accordingly, this study adopts a combined indicator of the number of researchers and the number of patents authorized by the enterprise to indicate the enterprise's technology integration capability, and proposes a hypothesis:

H1. Technology integration capacity of enterprises is positively associated with the L-CTIE-NEEs.

Within the L-CTIE-NEEs process, universities & research institutions provide talent training and cultural guidance support. Resource conversion capacity of universities & research institutions is their ability to convert received resources into scientific and technological talents and innovative culture. Universities & research institutions are the producers of knowledge and the source of human thought and knowledge innovation. They provide innovative ideas and knowledge for L-CTI, and have positively associated with L-CTI-NEEs [61]. Universities & research institutions have relatively complete disciplines and strong knowledge creation capabilities. They are national talent training and scientific research bases, providing talent guarantee for L-CTI-NEEs and improving the L-CTIE. According to the conceptual framework of absorptive capacity, Miller et al.(2017) described the multidimensional KT of universities and their beneficiaries in the pursuing of open innovative and commercially viable processes. The purpose is to overcome the barriers to effective knowledge management among local four spiral stakeholders in an open innovation ecosystem [62]. Universities & research institutions and enterprises share talents, advanced low-carbon technologies, advanced equipment and other resources through academic exchanges and scientific research projects, and realize the transformation of special technologies and scientific research results, which ensures the smooth progress of L-CTI. A good opportunity helps to improve the L-CTIE of enterprises [58]. Achieving a low-carbon economy depends to some extent on changing people's understanding. Universities & research institutions, with the support of government, cultivate the culture of L-CTI, guide the practice of L-CTI, and promote the L-CTIE-NEEs. The positive impact is beneficial to improving the L-CTIE of enterprises [61]. Based on it, this study utilizes the ratio of the number of invention patents that universities & research institutions participate in to the total number of invention patents to represent resource conversion capacity of universities & research institutions, and proposes a hypothesis:

H2. Resource conversion capacity of universities & research institutions is positively associated with the L-CTIE-NEEs.

Support intensity of government refers to the degree of government support for L-CTI-NEEs. Within the L-CTI process, firstly, government played a policy guidance and coordination role, and adjusted government procurement system and adjusted low-carbon technology. A series of development plans and measures, such as the technology patent review system [63], grant low-carbon technology protection and support policies [19], create a good technology innovation environment, and help improve enterprises' L-CTIE. Secondly, government has been supporting R&D and innovation in critical low-carbon technologies for a long time through large-scale R&D investment, promotion of pilot projects and industrial application of cutting-edge low-carbon technologies [64]. This can stimulate the vitality of L-CTI-NEEs, which is conducive to improving enterprises' L-CTI. Finally, government monitors and guides the L-CTI-NEEs. L-CTI faces problems such as high costs and being reluctant to commercialization. Government needs to implement effective supervision to reduce the obstacles to L-CTI-NEEs. Meanwhile, guiding various industries to vigorously promote the application of L-CTI. Accordingly, in this study the ratio of policy subsidies to R&D expenditure is used to express support intensity of government, and proposes a hypothesis:

H3. Support intensity of government is positively associated with the L-CTIE-NEEs.

Triple helix theory highlights that government, universities & research institutions and enterprises coordinate, supplement and cooperate with each other to jointly promote L-CTI and improve the low-carbon economy. L-CTI needs to count on leadership by government, implementation by enterprises, and facilitation by universities & research institutions [61]. Within the L-CTI process, the three will break boundaries and improve communication while ensuring their internal functions. The mutual penetration of each main function has formed the government-enterprises, government-universities & research institutions, enterprises-universities & research institutions and other bilateral hybrid forms, and government-enterprises-universities & research institutions trilateral hybrid form

[65]. Lai et al. also point out that a single driver has only a restricted effect on low carbon programs and requires synergy and co-operation between participants [10]. Leadership and support roles in the innovation process change over time, depending on the specific needs of the innovation. This will promote the L-CTIE-NEEs. Therefore, the larger the scale of the cooperation and the more frequent the exchanges between the three parties, the more beneficial it will be for the improvement of L-CTIE. Accordingly, this study expresses cooperation scale of government-enterprises-universities & research institutions by the number of bipartite or tripartite cooperation projects involving the government, enterprises, universities & research institutions, and proposes a hypothesis:

H4. Cooperation scale of government-enterprises-universities & research institutions is positively associated with the L-CTIE-NEEs.

3. Model construction

3.1. Research methods

1. DEA(BCC) model

Data Envelopment Model(DEA), under the premise of fully accounting for the optimal input-output plan of the DMU itself, uses the mathematical programming model to compare the relative efficiency of among the Decision-Making Units(DMUs) [66]. Following the practical characteristics of this study, L-CTI-NEEs is assumed to have variable returns to scale across time and space, and the question of how to minimize inputs for a given output is discussed. Therefore, the input-oriented DEA(BCC) model is chosen. The specific model settings are as follows:

Assuming there are f DMU (NEEs), and the evaluation index system includes x input-type indicators and y output-type indicators, so the DEA(BCC) model is:

$$min\left[\vartheta-\epsilon\left(\sum_{c=1}^{z}F_c^{+}+\sum_{a=1}^{x}F_c^{-}\right]\right.$$

$$s.t.\begin{cases}\sum_{b=1}^{y}P_{ab}\xi_b+F_c^{-}=\vartheta P_{ab0}\\ \sum_{b=1}^{y}Q_{cb}\xi_b+F_c^{+}=Q_{cb0}\\ \sum_{b=1}^{y}\xi_b=1,\xi_b\geq 0,b=1,2,\cdots,y.\\ F_c^{+},F_c^{-}\geq 0,a=1,2,\cdots,x;b=1,2,\cdots,z\end{cases} \tag{1}$$

Among them, P_{ab} represents the a th input of the b th DMU; Q_{cb} represents the c th input of the b th DMU; F_c^{+},F_c^{-} represent the corresponding input and output slack variables; ϑ is the efficiency value of the b th DMU; ϵ the introduced non-Archimedean infinitesimal variable.

2. Malmquist index model

Fare et al. with reference to Refs. [66,67] constructed the Malmquist productivity index to measure changes in production efficiency. The model of the Malmquist index is:

$$M\left(i^s,j^s,i^{s+1},j^{s+1}\right)=\left[\frac{H^{s+1}\left(i^s,j^s\right)}{H^s\left(i^{s+1},j^{s+1}\right)}\times\frac{H^{s+1}\left(i^{s+1},j^{s+1}\right)}{H^s\left(i^s,j^s\right)}\right]^{1/2} \tag{2}$$

Among them, H^s and H^{s+1} are the relative efficiencies of DMU in the reference period and the technical level in the period respectively. When $M(i^s,j^s,i^{s+1},j^{s+1})>1$, it indicates that the total factor productivity level has increased during the period s to $s+1$. When $M(i^s,j^s,i^{s+1},j^{s+1})<1$, it indicates that the total factor productivity level has decreased during the period s to $s+1$. Further Malmquist index decomposition is:

$$M=EFFCH\times TECH=PECH\times SECH\times TECH \tag{3}$$

that is:

$$M\left(i^s,j^s,i^{s+1},j^{s+1}\right)=\frac{H^s\left(i^s,j^s\right)}{H^{s+1}\left(i^{s+1},j^{s+1}\right)}\left[\frac{H^{s+1}\left(i^s,j^s\right)}{H^s\left(i^{s+1},j^{s+1}\right)}\times\frac{H^{s+1}\left(i^{s+1},j^{s+1}\right)}{H^s\left(i^s,j^s\right)}\right]^{1/2}$$

where $EFFCH$ is an index of technical efficiency change. If $EFFCH>1$ indicates that DMU has approached the production feasibility boundary between s and $s+1$. If $EFFCH<1$ indicates that the DMU is far from the production possibility boundary during this period.

Meantime, it is the product of pure technical efficiency(PECH) and scale efficiency(SECH). *TECH* is an index of technological progress change index. If $TECH > 1$ indicates that the production frontier moves forward at period s to $s+1$.

3. Tobit model

In order to study the L-CTIE-NEEs more scientifically and clearly, analyzing its influencing factors, this study uses the DEA(BCC) model to measure various efficiency values as dependent variables, because they are restricted variables(values between 0 and 1). Therefore, Tobit model was applied to complete the regression analysis.

$$y_i = \begin{cases} \beta x_i + \varepsilon_i & y_i^* \geq 0 \\ 0 & y_i^* \leq 0 \end{cases}$$

Where x_i is the independent variable, y_i is the dependent variable, y_i^* is the restricted variable, β is the model parameter, and $\varepsilon_i \sim (0, \sigma^2)$ is the random interference term.

4. DEA (BCC)-Malmquist-Tobit method

This study examines L-CTIE and influencing factors of NEEs, constructs an input-output indicator system, and uses DEA(BCC) model to validly evaluate the EFFCH, PECH, SECH of *DMU* to conduct difference analysis. As a static analysis method, the DEA(BCC) model cannot reveal the dynamic development trend of L-CTIE-NEEs. Therefore, the Malmquist index model was adopted to obtain an analysis of changes in L-CTIE of different NEEs. Meanwhile, Coelli proposed a two-step method [68] and constructed a DEA (BCC)-Malmquist-Tobit method for L-CTIE-NEEs to scientifically and clearly study its impact. To carry out a comprehensive analysis of the L-CTIE and the factors influencing NEEs from both dynamic and static aspects.

3.2. Indicator selection and data sources

The key to evaluating the L-CTIE-NEEs is the selection of appropriate evaluation indicators. Indicators should be selected based on science, comparability and availability. Refer to and learn from the rich research results of scholars [11,19,69], the input-output evaluation index system of L-CTIE-NEEs is established. In line with triple helix theory, considering input-output characteristics of L-CTI-NEEs, following the DEA operating conditions where the number of DMUs is not lower than the sum of the number of input-output indicators.

Input indicators: human resources and capital are the most basic elements of corporate innovation investment [19,70]. Corporate scientific research staff is the critical mainstay of innovation, leading the way, and can truly reflect the true situation of L-CTIE-NEEs. R&D expenditure is the most direct performance of enterprise R&D investment, which could objectively reflect the situation of L-CTI-NEEs. Meanwhile, referring to previous research results [70,71], this study selects R&D staff to total employees ratio and R&D expenditure to operating income ratio, respectively as L-CTI human resources and capital resources input indicators.

Output indicators: low-carbon technological achievements are the most intuitive reflection of L-CTI. Usually, the number of patent grants or patent applications is chosen to measure technological achievements [63]. This study believes that the former is considered to be a better indicator of the level of L-CTI than the latter. Therefore, number of granted technology patents is selected to measure the enterprise's ability to achieve L-CTI. L-CTI application capabilities are the ability to supply low-carbon technology, being accepted and recognized by the market. The low-carbon technology asset ratio reflects efficiency of enterprise's low-carbon technology R&D results, and is embodiment of the enterprise's L-CTIE [19,69]. Therefore, the low-carbon technology asset ratio is selected to measure the enterprise's ability to supply L-CTI results. Table 2 shows explicit evaluation indicators.

In line with the research objectives of this study and the theoretical analysis above, and given the availability of data and the measurability of the indices, 12 NEEs(see Table 3 for more information) have been selected to be DMUs. Among them, by industry distribution, it includes new energy integrated groups(5), solar energy(2), wind energy(2), automotive new energy power enterprises (2), and biomass energy enterprises(1). By type of enterprise, it includes central enterprises(2) and private enterprises(10). The data used was from the enterprise annual report and CSMAR database from 2010 to 2020, and the selected missing values were processed.

Table 2
L-CTIE measurement indicators for NEEs.

Indicator type	First level indicator	Secondary quantitative index
Input indicators	L-CTI human resources	R&D staff to total employees ratio
	L-CTI capital resources	R&D expenditure to operating income ratio
Output indicators	L-CTI capabilities	Number of granted technology patents
	L-CTI application capabilities	Low-carbon technology asset ratio

Table 3
The EFFCH, PECH and SECH of L-CTI-NEEs (2010-2020).

Enterprise	EFFCH	PECH	SECH
Sinovel Wind Power(SWP)	0.197	0.434	0.391
Goldwind Science & Technology(GST)	0.640	0.719	0.803
DaTang Corporation(DTC)	1.000	1.000	1.000
HuaNeng Group(HNG)	0.945	0.973	0.967
BYD	0.838	0.838	1.000
EG Photovoltaic(EGP)	0.412	0.612	0.683
LinYang Energy(LYE)	0.103	0.223	0.455
Ja Solar Holding(JSH)	0.316	0.603	0.601
ZhongTong Bus(ZTB)	0.417	0.584	0.715
SunGrow Power(SGP)	0.427	0.571	0.819
ENN Group(ENNG)	0.340	0.505	0.575
XiangTan Electric(XTE)	0.604	0.719	0.787
Mean	0.520	0.648	0.733

3.3. Empirical test and result analysis

3.3.1. Static analysis based on DEA(BCC) model

Calculations were carried out using the DEAP2.1 to derive the EFFCH, PECH and SECH for L-CTIE-NEEs from 2010 to 2020.

On the whole, the EFFCH for L-CTI-NEEs from 2010 to 2020 is moderate, with a mean of 0.520 and a PECH mean of 0.733, which is higher than the SECH mean of 0.648.

From an enterprise perspective, DTC's EFFCH reaches 1 on the frontier, and both PECH and SECH, indicating a high level of L-CTIE, indicating that it has high independent R&D capabilities and its input factors get fully utilized, fully leveraging the advantages of the enterprise and its products. HNG, BYD, GST, and XTE followed closely behind and exceeded the average overall efficiency of 0.520, indicating that the L-CTIE of these four enterprises is considerable. But at the same time, it also shows that the innovation model of the enterprise is deviated from the strategic goal and innovation investment, and needs to be adjusted according to the development of the enterprise to continuously stimulate the innovation power of the enterprise. The other seven enterprises are lower than the average. Among them, SWP and LYE are at a low level, with EFFCH of 0.197 and 0.103 respectively. It means that the L-CTIE is low, indicating that enterprises need to optimize the allocation of innovation input factors.

DTC, HNG, BYD, GST, and XTE exceed the average PECH of 0.648. In particular, DTC has reached PECH, indicating it possesses a high level of technical management and optimal use of resources. However, other enterprises have not reached the average value of PECH, among which LYE is the lowest, which indicates that there is a waste of resources or unreasonable resource input in its technical management.

The SECH of DTC and BYD is 1, and DEA is effective. It indicates that input-output structure of enterprise technological innovation is relatively reasonable, and input-output of technological innovation increases synchronously. This is mainly due to the scientific and effective management methods of enterprises. HNG, SGP, GST and XTE are higher than the average scale efficiency of 0.733, while the other seven enterprises are in the range of 0.391–0.715, of which SWP is the lowest. It shows that enterprises may have problems such as a complex product structure and high production costs, so they should improve the level of input-output allocation.

3.3.2. Dynamic analysis based on malmquist index

The dynamic change trend of the L-CTIE-NEEs can be reflected in the Malmquist index. Therefore, the dynamic variations and heterogeneity of technological innovation efficiency of the sample enterprises from 2010 to 2020 were calculated and analyzed using DEAP2.1.

Table 4 shows that the average value of TFPCH is greater than 1, indicating that L-CTIE-NEEs has a favourable development trend from 2010 to 2020, with an average annual growth rate of 25.4%. Malmquist index is decomposed into EFFCH and TECHCH. The

Table 4
Annual average Malmquist index and decomposition of NEEs.

Enterprise	EFFCH	TECHCH	PECH	SECH	TFPCH
Sinovel Wind Power(SWP)	0.522	1.491	0.783	0.666	0.778
Goldwind Science & Technology(GST)	0.742	1.631	0.925	0.801	1.209
DaTang Corporation(DTC)	1.000	1.253	1.000	1.000	1.253
HuaNeng Group(HNG)	1.000	1.380	1.000	1.000	1.380
BYD	0.875	1.116	1.000	0.875	0.977
EG Photovoltaic(EGP)	0.829	1.634	0.772	1.074	1.355
LinYang Energy(LYE)	0.709	1.630	0.751	0.944	1.156
Ja Solar Holding(JSH)	0.950	1.711	1.039	0.915	1.626
ZhongTong Bus(ZTB)	0.824	1.615	0.778	1.059	1.331
SunGrow Power(SGP)	0.819	1.711	1.000	0.819	1.401
ENN Group(ENNG)	0.741	1.454	0.772	0.959	1.077
XiangTan Electric(XTE)	0.866	1.732	0.984	0.879	1.500
Mean	0.823	1.530	0.900	0.916	1.254

average annual growth rate for the former was −17.7% and for the latter 53%. It can be seen that the growth of L-CTIE-NEEs is predominantly motivated by technological advances. The EFFCH decomposition results show that the growth rates of both PECH and SECH are negative, but the former is lower than the latter, which suggests that there is still a lot of room for improvement in the management efficiency of L-CTI-NEEs. Specifically, requires continuous improvement of innovation utilization rate, strengthening of carbon-saving technology market construction, optimization of input-output allocation, and gradual improvement of scale efficiency.

Among the 12 NEEs, 10 of them have a positive increase in the all-factor Malmquist index, indicating that most enterprises have improved their L-CTIE during this period. The all-factor Malmquist index of JSH, XTE, SGP, HNG, and EGP is greater than 1 and higher than the average. Among them, JSH and XTE have grown faster, with growth rates of 62.6% and 50%, respectively. The growth rates of SGP, HNG, EGP and ZTB were comparable, with growth rates of 40.1%, 38%, 35.5% and 31.1% respectively. There are two enterprises with negative growth in the all-factor Malmquist index, namely SWP and BYD. After further decomposition, the TECHCH of the 12 NEEs is all greater than 1, indicating that with the support of local governments, the speed of low-carbon technological progress has been continuously increasing. From the perspective of EFFCH, only the two enterprises of DTC and HNG have a value of 1, and the other enterprises are less than 1.

Further decomposing them, technical and management level fluctuations, scale inefficiency are twin barriers to the growth of L-CTIE-NEEs. Low PECH and SECH are mutually inhibiting their contribution to L-CTIE-NEEs growth somewhat, meaning that they need to face the twin realities of fluctuating levels of technology and management and inefficient scale. Further analysis of the changes in the L-CTIE-NEEs from a dynamic perspective was carried out by mapping the dynamic trends over the period 2010-2020.

During the research period, the general changing trend of L-CTIE-NEEs is classified into three segments. First stage is from 2010 to 2014, during which the all-factor Malmquist index fluctuates steadily within a small range. Second stage is from 2014 to 2016, during which the all-factor Malmquist index shows a sharp rise and fall, reaching a peak of 2.069 in 2014-2015. Third stage is from 2015 to 2020, the all-factor Malmquist index returns to a stable level and shows a gradual increase in this stage. Meantime, as shown in Fig. 2, the trend in the change in TECHCH over the period 2010-2017 basically the same as the trend in the change in the all-factor Malmquist index, but the degree is different. This once again shows that the predominant factor in technological progress during this period was the increased efficiency of L-CTI-NEEs. However, the TECHCH from 2017 to 2020 started to decrease year by year. Combined with the trend of EFFCH changes, from 2010 to 2017, it only fluctuated only in the range of 0.877–1.047, and from 2017 to 2020, it increased rapidly year by year. This shows that starting from 2016 to 2017, NEEs have been catching up with L-CTI faster, but it may also be difficult for new low-carbon technologies to digest and absorb gradually, resulting in slower progress of low-carbon technologies. Further decomposing and analyzing the trend of changes in EFFCH. It can be seen that it is affected by the combined effects of changes in PECH and SECH. In the period 2010-2017, they began to rise in varying degrees. It indicates that the majority of NEEs have realized the problems of technology level, management level, and innovative resource utilization, and have begun to actively take relevant measures. This is in keeping with changes in the social and economic environment and government's policy direction for new energy development. Since 2009, government has upgraded the new energy industry from "active guidance" to "strategic emphasis", and further formulated the "Tenth Five-Year Plan" on the development of new energy and renewable energy industries. At the same time, 2016 is the first year of the "Thirteenth Five-Year Plan". In the support of government and society, NEEs adhere to the idea of diversified development, constantly break through their own development problems, and strive to promote the low-carbon economic development.

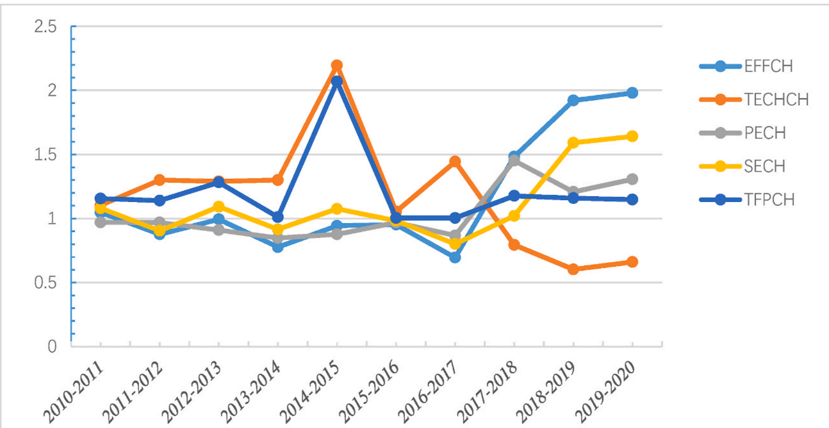

Fig. 2. The dynamic change trend of L-CTIE-NEEs from 2010 to 2020.
Note: EFFCH is technical efficiency. TECHCH is technological progress. PECH is pure technical efficiency. SECH is scale efficiency. TFPCH is total factor productivity.

3.4. Research on influencing factors based on tobit regression model

DEA model can be effective in estimating the allocation efficiency of inputs-outputs, but it is impossible to determine which factors affect the allocation efficiency. Tobit model can effectively solve this problem. To further explore the specific conditions of L-CTIE determinants of NEEs, the theoretical hypotheses of 2.2 are verified. The dependent variables are EFFCH, PECH and SECH of the L-CTI of each NEEs from 2010 to 2020 determined by the DEA model. The independent variables are technology integration capacity of enterprises(the combined indicator of the number of researchers and the number of patents authorized by the enterprise), resource conversion capacity of universities & research institutions(the ratio of the number of invention patents that universities & research institutions participate in to the total number of invention patents), support intensity of government(the ratio of policy subsidies to R&D expenditure), and cooperation scale of government-enterprises-universities & research institutions(the number of bipartite or tripartite cooperation projects involving the government, enterprises, universities & research institutions). Values for each independent variable are calculated using data from 12 NEEs from 2010 to 2020. Stata11.0 to perform regression analysis of the Tobit model's influencing factors with the following results see Table 5.

The results show that the EFFCH, PECH and SECH of L-CTIE-NEEs are significantly positively affected by technology integration capacity of enterprises, which has verified H1. It shows that technology integration capacity of enterprises have a dominant role to play in improving the L-CTIE-NEEs, and simultaneously affects the efficiency of innovation resource acquisition and resource allocation. This is consistent with the findings of [72].

Resource conversion capacity of universities & research institutions on PECH of L-CTIE-NEEs is significantly positive. It shows that resource conversion capacity of universities & research institutions provides support for L-CTI-NEEs with technical knowledge and talents, improving the L-CTIE. This is in line with the research conclusions of [73]. Therefore, the bilateral cooperation between universities & research institutions and enterprises should be strengthened, and the work of knowledge sharing and cooperation and personnel training should be continuously deepened.

The EFFCH, PECH and SECH of L-CTIE-NEEs are significantly positively affected by support intensity of government, which has verified H3. It shows that government funding and talent investment have a supportive role in improving the L-CTIE-NEEs. Concurrently, government should remain in the leading position and introduce appropriate preferential policies to promote the transformation and utilization of more scientific research results. This is in line with the research conclusions of [19,74].

The EFFCH, PECH and SECH of L-CTIE-NEEs are significantly positively affected by cooperation scale of government-enterprises-universities & research institutions, which has verified H4. It shows that the closer the tripartite relationship and the greater the level of cooperation, the greater the benefit of NEEs to improve L-CTIE. It also shows that triple helix theory can provide an objective and reasonable theoretical basis for L-CTIE-NEEs. Practical requirements for low-carbon development. This is in line with the research conclusions of [65,74].

4. Discussion

This article introduces the triple helix theory and proposes the construction of the DEA(BCC)-Malmquist-Tobit method. It conducts empirical research on the L-CTIE-NEEs and its influencing factors from two perspectives: static and dynamic. Solved the following three issues.

Question 1: DEA(BCC) model was deployed to examine the input-output combination of enterprises, fully understanding the real situation of each new energy enterprise, and the analysis results are consistent with the real market situation. With regard to the selection of indicators, a targeted screening of indicators was carried out in accordance with the research by Lin et al. [11], Feng et al. [21] and Chen et al. [29]. For investment indicators, Deng et al. [30] believes that human resources and capital are the most basic elements of enterprise innovation investment, which has also been recognized and validated by the literature [21,31]. Therefore, this study also selects investment indicators from these two aspects. For output indicators, consistent with the research in Sovacool [23], believing that the number of patents obtained better reflects the level of the enterprise than the number of applications. The decision to choose number of granted technology patents and low-carbon technology asset ratio has also been recognized by relevant experts. Finally, input-output indicators were determined, which can truly reflect the input-output status of L-CTI-NEEs.

Question 2. Malmquist model was applied to calculate the productivity and technological progress of NEEs from 2010 to 2020, fully understanding the changes in technological efficiency of NEEs over the past decade. The research results found that low-carbon technology development of NEEs and Chinese government policies are closely related. Supported by policy planning, NEEs are vigorously innovating low-carbon technologies. It indicates that policies play an indispensable part in the low-carbon technology

Table 5
Tobit regression results.

Influencing factors	EFFCH(M1)	PECH(M2)	SECH(M3)
Constant term	0.4502***	0.7597***	0.6492***
Technology integration capacity of enterprises	0.7987**	0.6884**	0.6439***
Resource conversion capacity of universities & research institutions	0.0478	1.0687**	0.0582
Support intensity of government	0.0181***	0.2675**	0.0263***
Cooperation scale of government-enterprises-universities & research institutions	0.1483*	0.0143**	0.0189*

Note: *, **, *** indicate significant at the level of 1%, 5%, and 10%, respectively.

development of NEEs [16,18], especially government encouragement and supportive policies [22,23].

Question 3. Tobit model was carried out to explore the influencing factors of L-CTIE-NEEs. Unlike existing studies that only measure the allocation efficiency of inputs and outputs, this study further explores which factors affect allocation efficiency. This is very novel. In Tobit model, the dependent variables are the values of EFFCH, PECH and SECH for various sorts of NEEs. The independent variables follow triple helix theory, starting from the three innovative entities of NEEs, selecting multiple influencing factors for exploration and verification. Compared with the research of others, it is more advantageous in developing more focused L-CTI suggestions for NEEs.

5. Conclusions

5.1. Results and recommendations

This study constructs the DEA(BCC)-Malmquist-Tobit method and empirically investigates L-CTIE-NEEs and its influencing factors from two aspects: static and dynamic, using panel data of 12 NEEs from 2010 to 2020. From the perspective of static calculation of innovation efficiency, the average EFFCH of L-CTI-NEEs was at a medium level, and the average SECH was superior to the average PECH. Among them, the average EFFCH, PECH and SECH of DTC are all valid for DEA, while the SWP, EGP, LYE, JSH, ZTB and ENNG's average EFFCH, PECH and SECH are all smaller than their respective average values. It shows that the L-CTIE of various NEEs is quite different, the level of L-CTI is uneven, and the development is unbalanced. From the perspective of dynamic calculation of innovation efficiency, the L-CTIE-NEEs all-factor Malmquist index changes, possesses the characteristics of phased changes, gradually returns to stability and shows a growth trend. The results of Malmquist index decomposition indicate that changes in the value of TECH are important, with changes in PECH and SECH being supportive, while changes in EFFCH are relatively constant.

Analyzed from the factors affecting innovation efficiency, technology integration capacity of enterprises, support intensity of government and cooperation scale of government-enterprises-universities & research institutions play a crucial part in promoting the EEFCH, PECH and SECH of L-CTIE-NEEs. Resource conversion capacity of universities & research institutions only promotes PECH. Based on triple helix theory, the negotiations between governments, enterprises and universities & research institutions form the core of the L-CTI system, which promotes the continuous increase of the L-CTI spiral. In the multi-spiral ascent, they both remain relatively independent of each other, and they can interact effectively with each other for mutual benefit. They coordinate, complement and cooperate with each other, forming a spiral ascending model in which three forces come together to promote the L-CTI-NEEs.

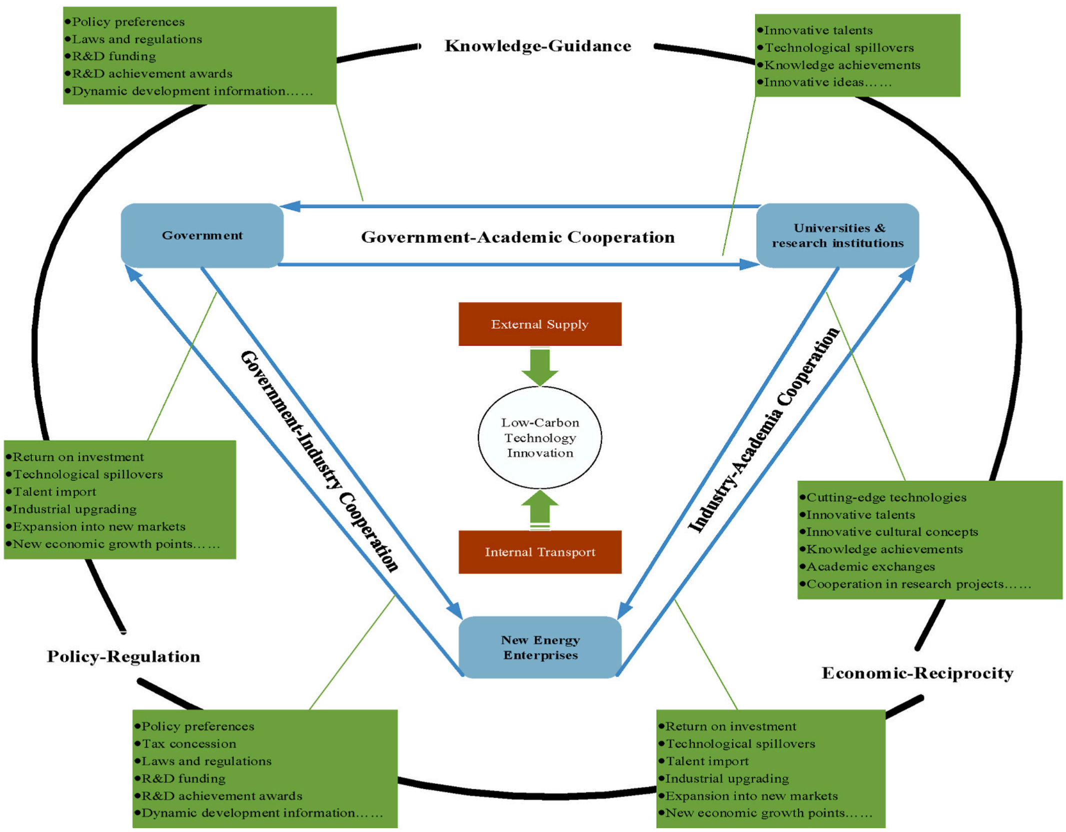

Fig. 3. The triple helix model of L-CTI-NEEs.

Depending on the results of this study, several recommendations are made for improving L-CTI-NEEs based on triple helix theory see Fig. 3:

(1) On the enterprises side. In contrast to SMEs(small and medium-sized enterprises) with poor energy conservation measures, unregulated energy control, poor quality of staff energy control, weak energy statistical bases, obsolete technology and equipment, and low efficiency in energy consumption [75], NEEs are more likely to be able to innovate in low-carbon technologies areas. Firstly, NEEs should comprehensively balance and compare their own innovation conditions, combining development opportunities, market capacity and production efficiency, adjusting corporate L-CTI plans, improving input-output allocation, and overcoming the obstacles of scale inefficiency to the growth of L-CTIE. Secondly, NEEs continue to increase investment in L-CTI. On the one hand, they have to increase R&D investment by plan, stimulate corporate R&D capabilities and innovation motivation, increase research and development in core technologies. On the another hand, strengthening talent introduction and cultivation, establishing effective talent assessment and reward mechanisms, and creating a favourable development environment and policies for innovation teams. At the same time, enterprises should attach importance to building innovation culture, stimulating innovation potential and improving innovation quality. Thirdly, NEEs should ensure the coordinated development of low-carbon technology R&D and technology application. They should pay attention to the effective matching of low-carbon technology R&D with market demand. Specifically, it includes improving the efficiency of innovation transformation, strengthening the construction of enterprise technology learning system, and improving the guarantee mechanism for technology transformation. Fourth, NEEs should increase opportunities for bilateral or tripartite cooperation with government and universities & research institutions. Especially, talent advantages of universities & research institutions and policy advantages of government can be used to deal with L-CTI problems, to overcome the obstacles in the development of new energy, and to enhance L-CTIE. Fifth, NEEs should actively learn and draw from the valuable experience of advanced enterprises, transfer part of the risks in the technology innovation process to third-party service enterprises, and improve the L-CTIE by strengthening the management of the L-CTI process and output effects.
(2) On the universities & research institutions side. New energy has a renewable character and requires high technological innovation. Universities & research institutions are the main bearers of L-CTI and should play an important role. They should actively engage in bilateral cooperation with NEEs, integrate new methods and ideas based on practical experience, improve L-CTI, and focus on cultivating talent innovation awareness and abilities. They can also participate in applying for government-funded projects by emphasizing technology transfer, transforming scientific and technological achievements to gain more research funding. Simultaneously, it is also important for universities & research institutions to raise awareness about protecting intellectual property and promoting and applying low-carbon technology achievements.
(3) On the government side. Unlike most enterprises, NEEs are concerned with the long-term survival and development of mankind and therefore require systematic strategic planning by government. Government should encourage and supervise NEEs. For one thing, government should strengthen its support towards NEEs, innovate investment forms, and convert direct capital investment into low-carbon investment. This could facilitate the flow of low-carbon technologies, promote R&D efficiency and transfer of results. For example, government can establish a fiscal incentive mechanism to give tax incentives to NEEs for L-CTI projects, and give spending concessions in terms of income tax and other tax reductions. Government could establish a financial subsidy mechanism and innovate the use of financial funds to encourage L-CTI-NEEs. It can also improve financial services support and introduce corresponding incentive policies to encourage commercial banks to provide preferential loans to L-CTI-NEEs. For another, government as a regulator, should further increase supervision and penalties so that a favourable innovation environment can be provided for L-CTI-NEEs. For example, it should prevent technology theft and plagiarism, improve the review and authorization procedures for L-CTI, and protect corporate intellectual property rights and patented technologies.

5.2. Limitations and future research

However, there remain some limitations. The one is the selection of sample data. Firstly, there are certain difficulties in collecting data on technological innovation in NEEs. There are differences in the data reported by different enterprises and it is necessary to select consistent indicator data based on the enterprises' annual report. Therefore, further consideration is needed to determine whether these consistent indicators truly reflect the true situation of enterprises. Secondly, there is a time lag in the data, which fails to timely reflect the realities of the enterprise development. The second is the selection of indicators. Firstly, due to the limited theoretical level, the research on L-CTIE-NEEs is not comprehensive enough, and there may be a problem of incomplete measurement indicators selected. Secondly, in terms of quantification of indicators, there may be multiple measurement indicators for a certain capability of the enterprise, but only one can be selected. Although this study provides sufficient grounds, further consideration of the objectivity of these grounds is required in the future. For instance, both the number of patents authorized by enterprise and the ratio of enterprise's R&D investment to its main business income can be used as indicators to measure technology integration capacity of enterprises, but this study chooses the former.

Therefore, in the next step of the study, we must fully consider the above issues. Firstly, we can attempt using big data to find more data of NEEs. At the same time, the sample amount can be increased to improve the generality of the research results. Alternatively, a case study method can be used to conduct in-depth research on a NEE. Secondly, continuously enrich its theoretical knowledge and consider from multiple perspectives whether there are other factors that affect the L-CTIE-NEEs. For example, whether and how consumers as the main body play a role in continuously enriching research on technological innovation in NEEs.

Author contribution statement

Yu Guo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Giulia Bruno: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Deming Zhang: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Kaikai Han: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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