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Carbon emission reductions under global low-carbon technology transfer and its policy mix with R&D improvement

Gaoxiang Gu [a, *], Zheng Wang [b, c, **], Leying Wu [d]

[a] Population Research Institute, East China Normal University, Shanghai, 200241, China
[b] Institutes of Science and Development, Chinese Academy of Sciences, Beijing, 100080, China
[c] Key Laboratory of Geographical Information Science, Ministry of State Education of China, East China Normal University, Shanghai, 200241, China
[d] Key Research Institute of Yellow River Civilization and Sustainable Development & Collaborative Innovation Center on Yellow River Civilization jointly built by Henan Province and Ministry of Education, Henan University, Kaifeng, 475001, China

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A B S T R A C T

In this study, we have developed a new integrated assessment model named CIECIA-TD to study the carbon reductions and climatic and economic impacts of global low-carbon technology transfer and its policy mix with R&D improvement. Compared with its base model, CIECIA, CIECIA-TD comprises a bottom-up technology transfer and diffusion mode for depicting the individual technology transfer behaviours. The results show that the technology transfer has significant reduction and warming mitigation effects. However, it is insufficient for achieving the 2 °C mitigation goal. The technologies transfer frequently between developed countries, achieving significant carbon reductions when the low-carbon technologies are fully shared around the world, whereas reductions of developing countries are mainly limited by their knowledge stocks and R&D investments. Climate policy mix that combines technology transfer and R&D improvement can achieve the 2 °C mitigation target. However, the economic benefits of countries are eroded as the price of global warming mitigation under this policy mix.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) defined technology transfer as the broad set of processes covering the flows of know-how, experience, and equipment amongst different stakeholders [1]. It has been widely recognised that the development, transfer, and application of low-carbon technologies is one of the key ways in which the carbon emissions of countries, especially those emerging economies that are experiencing unprecedented levels of economic growth, can be either reduced or avoided [2–4]. The principle of *Common but Differentiated Responsibilities* of the United Nations Framework Convention on Climate Change (UNFCCC) underlies the responsibility of developed countries to transfer green technology to developing countries [5–7]. Technology transfer was also an important element of the Kyoto Protocol [6,8]. The Clean Development Mechanism (CDM) was intended to help achieve the mitigation commitments of the Annex 1 parties by transferring cleaner technology to developing countries through financing emission reduction projects [9–11].

In the post-Kyoto climate conferences, technology transfer was always considered to be an appropriate mitigation action for developing countries, and the importance of the enhancement of technology development and transfer to developing country parties to enable action on mitigation and adaptation was affirmed and underlined repeatedly in the climate agreements such as the Bali Action Plan, the Copenhagen Accord, and the Cancún Agreements [12–14]. In the Paris Agreement, nationally determined contributions (NDCs) were adopted as the greenhouse gas reduction plans of countries in the short and medium term [15]. The main emitters among the developing countries, including China, Brazil, India, South Africa, Mexico, and Turkey, have written low-carbon technology support and cooperation from developed countries into the requests of conditional reductions of their INDC/NDCs. In its NDC, India suggested a mechanism in which technology and innovation should be turned into an effective instrument for global public good rather than as a commercial opportunity if climate change is a calamity to which mankind must adapt. Therefore, it is

* Corresponding author.
** Corresponding author. Key Laboratory of Geographical Information Science, Ministry of State Education of China, East China Normal University, Shanghai, 200241, China.
E-mail addresses: gxgu@soci.ecnu.edu.cn (G. Gu), wangzheng@mail.casipm.ac.cn (Z. Wang).

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of great significance to study the impacts of international low-carbon technology transfer and its policy mix on carbon reductions and the economic development of countries in the context of global carbon reduction cooperation.

At present, studies and discussions about low-carbon technology transfer focus on institutional factors such as patent systems and intellectual property rights, and their impacts on international low-carbon transfer [16]. Ockwell et al. summarized six policy factors in the international low-carbon transfer from developed to developing countries based on a UK-India collaborative case of two low-carbon technologies [3]. Greaker and Rosendah studied the effects of stringent strategic environment policy on abatement technology production and spill-over based on a three-stage game model [17]. Ockwell et al. analysed the conflict between economic development and low-carbon transfer, and discussed negative impacts of the proprietary intellectual property rights on the low-carbon technology transfer [18]. Pueyo identified the enabling factors for low-carbon technology transfer to developing countries by analysing 10 case studies in Chile, and proposed relevant policy recommendations [4]. Iizuka discussed the role of technology transfer in the transition process of the rapid growing emerging economies towards low-carbon development by presenting an example of solar photovoltaic (PV) energy in China [19]. Rai et al. studied the effects of intellectual property regimes on the diffusion and transfer of three key low-carbon technologies (solar photovoltaics, electric vehicles, and integrated gasification combined cycle) in emerging economies like China and India [20]. These studies analysed and indicated the concepts, processes and impact factors of low-carbon technology transfer and its relevant regimes in detail. However, the calculations of economic impacts and carbon emission reductions during the process of technology transfer were not involved and therefore cannot be assessed quantitatively.

The assessment and analysis of carbon reductions and climatic-economic effects of international low-carbon technology transfer are a complex interdisciplinary problem. This analysis includes process modelling of low-carbon technology development and transfer, such as technology investment, research and development, adoption, transfer and diffusion. The interactions between technology development and other factors such as economic growth, energy use, carbon emission, environment change, policy and regime should also be depicted in the model due to the complexity of this issue. Integrated assessment models (IAMs) that comprise theories, approaches and models of multiple disciplines are suitable for solving these problems. Although many current IAMs have integrated modules of technology innovation, diffusion and adoption based on different theories, some shortcomings still exist in those models [21,22].

Many bottom-up energy models such as the LEAP (The Low Emissions Analysis Platform) [23] and LBNL (Lawrence Berkeley National Lab) China End-Use Energy Model [24] depict abundant specific low-carbon technologies in the areas of industrial production, equipment efficiency and residential appliance usage. However, these models consider the technological development process exogenously. In addition, in many of these models, the economic growth in different scenarios is also assumed and projected exogenously. Although top-down models such as AIM (The Asian-Pacific Integrated Model) [25], C-GEM (Carbon-Generic Estuary Model) [26] and EPPA (The MIT emissions prediction and policy analysis model) [27,28] adopted the CGE (Computable General Equilibrium) model to endogenize their economies, their parameter values of applied autonomous energy efficiency improvement (AEEI), which are crucial for depicting the natural diffusion of low-carbon technologies, can only reflect the carbon reduction effects of technology development at the macro level [29]. Thus, to depict the spread and application of some specific advanced technologies, e.g., carbon capture storage, biomass generation and the gas combined cycle, C-GEM introduced exogenous technology diffusion rates to determine their diffusion and penetration. EPPA also incorporated a non-extant technology source model that represented the endogenous change of those advanced low-carbon technologies when they penetrated supply markets.

In other hybrid models, Kypreos introduced an endogenous technology progress approach into MERGE (Model for Evaluating Regional and Global Effects of GHG Reductions) [30]. In this model, the R&D inputs of technologies were reduced by learning-by-doing, and low-carbon technology transfer was realized by market incentives to improve the market shares of low-carbon technologies. A similar approach was adopted by WITCH (World Induced Technical Change Hybrid) model, in which the R&D costs of those existing technologies decreased by technology transfer based on empirical curve fitting methods [31]. However, these approaches depicted the decline of R&D cost brought by technology diffusion by statistic results, lacking a micro mechanism of individual technology transfer behaviours. Hübler et al. designed an endogenous technology progress module including technology innovation, imitation and R&D input behaviours based on REMIND (Regional Model of Investments and Development) [22]. However, this technology diffusion mode is still at a macro level. The imitating rates of countries are determined by the global average technology level (world technology pool), and the technology learning and transfer behaviours at the micro level are not included. Therefore, this module still cannot satisfy the policy assessment and analysis of low-carbon technology. Gu and Wang incorporated an agent-based technology diffusion model into the top-down model CIECIA (Capital Industrial Evolution and Climate Change Integrated Assessment model) to reflect the sectoral technology transfer from developed to developing countries [32]. This model adopted the average low-carbon technology level of developed countries as the advanced technology source. However, its technology transfer process was highly simplified and incomplete, and the micro technology transfer behaviours between sectors were not depicted.

In summary, those bottom-up models lack a detailed macro-economic system and thus have shortcomings in their endogenous technology mechanism, which may generate enormous reality deviations. The models based on macro-economic models cannot reflect the micro-mechanism of technology development and adoption due to model simplification, and therefore cannot assess the effects of policies on the technology transfer process. For overcoming these shortcomings, this study combined the top-down IAM with bottom-up technology transfer and diffusion behaviours. In this study, the climate-economy IAM, CIECIA, was modified, and a new version named CIECIA-TD was developed. CIECIA adopted a multi-national-sectoral general equilibrium model as its economic core to depict the economic interactions between sectors in countries under global equilibrium conditions, and can analyse the climatic and economic impacts of carbon abatement measures [33]. On the basis of CIECIA, CIECIA-TD coupled the top-down general equilibrium model with an international low-carbon technology transfer and diffusion module that is based on individual imitating behaviours; furthermore, CIECIA-TD realized the micro mechanism of low-carbon technology diffusion at the sectoral level.

On the basis of CIECIA-TD, four scenarios have been designed to simulate the different trends of low-carbon technology transfer among sectors of countries in Section 3.1. Their carbon reduction effects and climatic–economic impacts have been studied in the context of current global carbon reduction cooperation. In Section 3.2, we describe two policy mix scenarios designed for achieving the global warming mitigation goal by combining low-carbon technology transfer with the R&D improvements.

2. Model and data sources

CIECIA comprises a multi-national-sectoral general equilibrium model developed from Jin [34] as its economic core and a global carbon cycle model, including three carbon cycles [35], as its climate module. The technology progress in CIECIA includes labour technology progress, knowledge accumulation, and process technology progress. In this study, low-carbon technology progress refers to process technology progress. Process technology progress refers to the craft technology innovations in the production process that lower the intermediate cost of a unitary product. According to Gu and Wang [32], process technology progress represents a broad concept of energy-saving technology, as the production of non-energy intermediate inputs also consumes energy.

In this study, a global technology diffusion and transfer mechanism based on individual technology learning behaviours has been adopted and incorporated into CIECIA to build CIECIA-TD for depicting the transfer and diffusion of low-carbon technologies between sectors of countries [32,36]. In this mechanism, the micro technology transfer behaviours include individual technology searching, selecting, learning and imitating, and adopting. Fig. 1 shows the basic structure of CIECIA-TD. For the range of this study, this section mainly introduces the parts that are closely related to process technology progress and low-carbon technology transfer; the detailed structure of the other parts of CIECIA can be obtained from Wang et al. [33].

2.1. Production

CIECIA employs a two-layered production function comprising the Leontief and the Cobb−Douglas production functions to depict the sectoral production. The sectoral gross output is composed of value added and intermediate inputs. The value added is formed by labour, fixed capital stock, and knowledge capital stock.

$$X_{i,t}^{j} = \min\left\{\frac{M_{1,i,t}^{j}}{a_{1,j,i,t}}, \ldots, \frac{M_{k,i,t}^{j}}{a_{k,j,i,t}}, \ldots, \frac{M_{I,i,t}^{j}}{a_{I,j,i,t}}, X_{i,j,t}^{*}\right\}, \quad k = 1, \ldots, I \tag{1}$$

$$X_{i,j,t}^{*} = \Omega_{i,j,t}\left(K_{i,t}^{j}\right)^{\alpha_i}\left(A_t^j L_{i,t}^{j}\right)^{1-\alpha_i}\left(Z_t^j\right)^{\beta_{j,t}^{Z}} \tag{2}$$

$$Y_{i,t}^{j} = \sum\nolimits_{k}^{I} M_{k,i,t}^{j} p_{k,t} + X_{i,t}^{j} p_{i,t} \tag{3}$$

where $X_{i,t}^{j}$ denotes the real value added in step t in sector i of country j; $M_{k,i,t}^{j}$ denotes the intermediate input k that sector i of country j actually uses in the production process; $a_{k,j,i,t}$ is the intermediate input coefficient; $X_{i,j,t}^{*}$ is the initial value added formed by labour, capital, and knowledge, though the real one is limited by the supply of intermediate inputs in Equation (1); $K_{i,t}^{j}$ is the fixed capital stock; $L_{i,t}^{j}$ is the labour force; A_t^j is the labour technological level; α_i is the output elasticity of fixed capital stock; Z_t^j is the

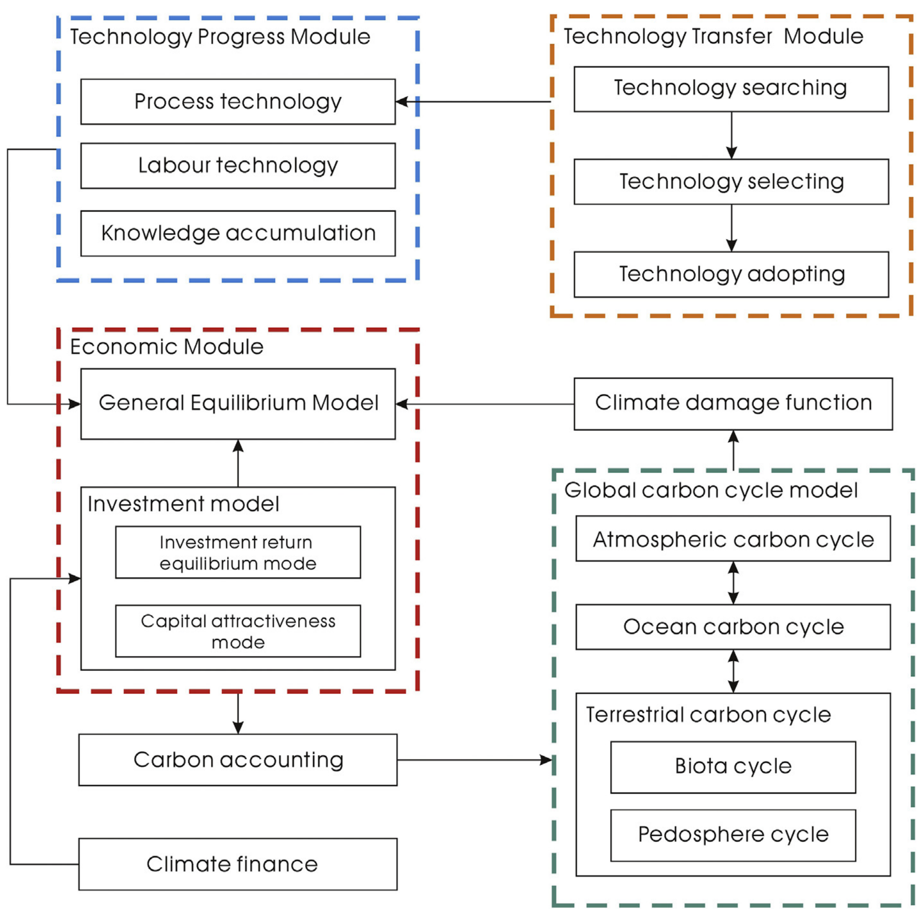

Fig. 1. The basic model structure of CIECIA-TD.

knowledge capital stock, $\beta^{Z}_{j,t}$ is the output elasticity of knowledge stock; $p_{i,t}$ is the product price, $\Omega_{i,j,t}$ is the damage factor for rising temperature, and $Y^{j}_{i,t}$ denotes the sectoral gross output.

Fixed capital stock is accumulated under the log-linear form [34,37]. Equations (5) and (6) reflect that the knowledge capital comes from the R&D inputs and depreciates over time. The direct energy R&D input is distinguished from the overall R&D investment according to Gu and Wang [32]. The knowledge stock and cumulative direct energy R&D expenditure are accumulated under the perpetual inventory method [32,38,39].

$$K^{j}_{i,t+1} = a\left(Ik^{j}_{i,t}\right)^{\varphi}\left(K^{j}_{i,t}\right)^{1-\varphi} \tag{4}$$

$$Z^{j}_{t} = (1-\delta_Z)Z^{j}_{t-1} + Iz^{j}_{t}, \quad Iz^{j}_{t} = \eta^{z}_{j,t}X^{j}_{t} \tag{5}$$

$$E^{j}_{t} = (1-\delta_E)E^{j}_{t-1} + Ie^{j}_{t}, \quad Ie^{j}_{t} = \eta^{e}_{j,t}X^{j}_{t} \tag{6}$$

$$\sum\nolimits_{j}^{J} Iz^{j}_{t} + \sum\nolimits_{j}^{J} Ie^{j}_{t} + \sum\nolimits_{j}^{J}\sum\nolimits_{i}^{I} Ik^{j}_{i,t} = I^{g}_{t} \tag{7}$$

where $Ik^{j}_{i,t}$ is the fixed capital investment, Iz^{j}_{t} is the R&D input, Ie^{j}_{t} is the direct energy R&D input, E^{j}_{t} is the cumulative direct energy R&D expenditure, I^{g}_{t} is the global investment, and η^{z}_{jt} and η^{e}_{jt} are the R&D investment rate and direct energy R&D investment rate, respectively. The Keynes–Ramsey utility is adopted to reflect economic power during scenario simulation [40].

$$U^{j}(T) = \sum_{t=1}^{T} (\beta+1)^{-t} Pop^{j}_{t} \frac{\left(C^{j}_{t}/Pop^{j}_{t}\right)^{1-\rho}}{1-\rho} \tag{8}$$

where $U^{j}(T)$ is the cumulative utility of country j by step T; C^{j}_{t} is the consumption; Pop^{j}_{t} is the national population; β is the discount rate; and ρ is the time preference of consumers. Cumulative utility is the key indicator for evaluating economic impact in this study.

2.2. Process technology progress

Process technology progress reflects the decrease of energy use and carbon emission demands during production from an input-output perspective. It represents a broad concept of energy-saving technology, as the intermediate input saving leads to energy saving and then reduces carbon emissions. Thus, it includes both direct and indirect energy-saving innovations in the production process.

The process technology progress model in CIECIA was developed from the model in Lorentz and Savona [41]. Each set of intermediate input coefficients $(a_{1,j,i,t},\ldots,a_{k,j,i,t},\ldots,a_{I,j,i,t})$represents a single process technology. This model adopts a looping stochastic logarithmic shock mechanism, in which every intermediate input coefficient in sectors of countries is randomly shocked by normal distributed numbers in a logarithmic form several times in every step. The new generated intermediate input coefficients will be accepted if the potential unitary production cost is lower than the former one. This process depicts a sector's self-selection of technology and reflects the evolution mode whereby the technological progress is the result of selection of enterprise for profit, rather than being just a slow, incremental process from the macrocosmic point [42]. This mechanism reflects both the randomness and autonomous nature of technological progress and adoption, and it is far closer to reality [32].

The technology shock for the intermediate input coefficient in every turn of every step can be given by:

$$\ln\left(a'_{k,j,i,t}\right) = \ln\left(a^{*}_{k,j,i,t,n}\right) + \varepsilon_{j,k,i,t,n}, \quad \varepsilon_{j,k,i,t,n} \sim N\left(0;\rho^{j}_{k,t}\right) \tag{9}$$

where $a'_{k,j,i,t}$ is the intermediate demand coefficient of intermediate product k in sector i of country j after n turns; $\varepsilon_{j,k,i,t,n}$ is the stochastic shock that obeys normal distribution; n denotes the turn number; $a^{*}_{k,j,i,t,n}$ is the intermediate demand coefficient of product k after n-1 turns; and $\rho^{j}_{i,t}$ is the variance of the stochastic shock.

After one turn, the new intermediate demand coefficient set $(a'_{1,j,i,t},\ldots,a'_{k,j,i,t},\ldots,a'_{I,j,i,t})$ will be adopted if its unitary production cost is lower than the former one:

$$\left(a^{*}_{1,j,i,t,n},\ldots,a^{*}_{I,j,i,t,n}\right) = \begin{cases} \left(a'_{1,j,i,t},\ldots,a'_{I,j,i,t}\right) & \text{if } \sum\nolimits_{k}^{I} a'_{k,j,i,t}p_{k,t} < \sum\nolimits_{k}^{I} a^{*}_{k,j,i,t,n-1}p_{k,t} \\ \left(a^{*}_{1,j,i,t,n-1},\ldots,a^{*}_{I,j,i,t,n-1}\right) & \text{Otherwise} \end{cases} \tag{10}$$

where $p_{i,t}$ is the price of product i in step t; $\sum_{k}^{I} a'_{k,j,i,t}p_{k,t}$ denotes the unitary production cost of the new set $(a'_{1,j,i,t},\ldots,a'_{I,j,i,t})$ in turn n, and $\sum_{k}^{I} a^{*}_{k,j,i,t,n-1}p_{k,t}$ means the unitary production cost of the former set.

According to Gu and Wang [32] and Wang et al. [33], ρ^{j}_{t} is related to knowledge capital stock; the value of ρ^{j}_{t} is determined by the ratio of knowledge stock in the total capital, and the energy R&D only affects the process technological progress of the energy sector.

$$\rho^{j}_{i,t} = \begin{cases} a^{\rho}\dfrac{Z^{j}_{t}+E^{j}_{t}}{Z^{j}_{t}+E^{j}_{t}+K^{j}_{t}} + b^{\rho} + c^{\rho}_{j,t} & \text{if } i = Enrg \\ a^{\rho}\dfrac{Z^{j}_{t}}{Z^{j}_{t}+K^{j}_{t}} + b^{\rho} + c^{\rho}_{j,t} & \text{otherwise} \end{cases} \tag{11}$$

where a^{ρ}, b^{ρ} are parameters, $c^{\rho}_{j,t}$ is an adjustment to the rate of process technological progress, and *Enrg* means the energy sector.

2.3. Technology transfer and diffusion

CIECIA-TD modified an agent-based innovation diffusion and spill-over model, and integrated it into CIECIA to depict the peer-to-peer technology transfer behaviours on the basis of its prototype in Gu and Wang [32]. The original agent-based model built by Wang et al. comprises an intellectual-property regime to protect innovation patents [36]. In that agent-based model, the concept of sequence innovation is adopted, and a complete mechanism including investment, technology R&D, patent protection, imitation and patent purchase is designed for depicting the life cycle of a technology patent including R&D, diffusion, adoption and obsolescence [36].

In CIECIA-TD, the technology transfer process comprises the processes of technology searching, selecting, learning, and imitating. This structure is in accordance with what IPCC emphasised, that is, technology transfer consists of the process of learning to understand, utilise, and replicate technology, including the capacity to choose it and adapt it to local conditions [1]. In this model, each sector in every country is regarded as both a potential technology provider and an imitator in technology transfer; each set of intermediate input coefficients in the market $\varpi^j_{i,t} = (a_{1,j,i,t}, \cdots, a_{k,j,i,t}, \ldots, a_{I,j,i,t})$ represents a single process technology (i.e., low-carbon technology) that can diffuse and transfer between the same sectors of countries.

Technology transfer does not mean that the recipient can adopt the advanced technologies directly. First, the transfer of technologies incurs costs, and recipient countries need to invest in order to be able to use the technology effectively [43]. It still takes time and money to absorb and adopt new technology [4]. Second, the intellectual property protection such as the patent regime will also hinder technology diffusion to some extent [4]. Kennedy and Basu generalised them into two barriers: the knowledge and investment barrier and the institutional barrier [44].

The sectoral technology transfer process in this model is mainly controlled by R&D acceleration s and technology transfer threshold W in the following Equations (12) and (18). The R&D acceleration reflects the imitator's ability to absorb knowledge and imitate technologies. It means the imitator can improve its R&D efficiency through technology transfer based on its own R&D ability.

The technology transfer threshold refers to the protection range of the patent regime. It divides the technology gap between the technology supplier and the recipient into two parts: the imitable one and the patent protected one. Technology imitation will be limited by the intellectual property regime during imitation according to the value of W. Thus, the transfer threshold represents the institutional barrier in the technology transfer process and indicates the degree of technology sharing.

2.3.1. Technology searching

In the technology searching step, the sectors need to search for a set of feasible advanced low-carbon technologies ϖ from the same sectors in all other countries. The searching criteria comprise the following two factors: the technological level and the economic level. Every sector is both a potential technology supplier and a potential recipient. If a sector in one country owns the most advanced process technology on the global level, it can only be a technology supplier in this step.

$$\varpi = \left\{ \varpi_K \middle| (1+W)c^k_{i,t} < c^j_{i,t} \text{ and } x^k_{i,t} > \omega x^j_{i,t},\ k \neq j \right\} \tag{12}$$

where ϖ_K is a feasible process technology for sector i in country j; $a_{k,j,i,t}$ is the intermediate input coefficient of sector i in country j for the product of sector k, unitary energy cost $c^j_{i,t}$ denotes the technology factor in the condition, while GDP per capita $x^j_{i,t}$ denotes the economic factor; and $(1+W)c^k_{i,t}$ denotes the lower bond of the imitation range, indicating that the unitary energy cost of the imitator must be $(1+W)$ higher than that of its potential supplier. It is worth noting that $x^k_{i,t} > \omega x^j_{i,t}$ represents an economic restriction on the feasible imitating target, where ω denotes the economic restriction parameter. Data from GTAP-9 and EIA show that in some sectors, the energy intensities in the least developed countries in 2007 are even lower than are those in the most developed countries with the most advanced low-carbon technologies, such as the USA, the EU, and Japan (see Appendix II). That is because those developing countries lack resources and intermediate products, rather than having higher technology levels.

The unitary energy cost $c^j_{i,t}$ of sector i in country j in Equation (12) comprises two parts: the direct energy cost in production of sector i in country j, and the indirect energy cost in production of the intermediate inputs of sector i in country j. According to the classic input–output model, the sectoral indirect energy consumption can be given according to the intermediate input matrix and the energy intensities of intermediate inputs. For simplification, the global average intermediate input coefficients of sectors have been adopted. The form of $c^j_{i,t}$ can be given as:

$$c^j_{i,t} = \overline{F}_t \left(I - \overline{\Theta}_t \right)^{-1} \Psi^j_{i,t} + a^j_{E,i,t} \tag{13}$$

where I denotes the identity matrix; $\overline{a}_{k,i,t}$ is the global average level of intermediate input demand for product k per product of sector i in step t; $\overline{a}_{E,i,t}$ is the average level of intermediate input demand for the energy product per product; $\overline{F}_t = \{\overline{a}_{E,1,t}, \cdots, \overline{a}_{E,i,t}, \cdots, \overline{a}_{E,I,t}\}$ is the row vector of the average intermediate input demand level for the energy product of sectors across countries in step t; $\overline{\Theta}_t$ is the average intermediate input coefficient matrix of sectors in step t; and $\Psi^j_{i,t} = \{a^j_{1,i,t}, \cdots, a^j_{k,i,t}, \cdots, a^j_{I,i,t}\}^T$ is the column vector of the intermediate input coefficient of sector i in country j in step t. $a^j_{E,i,t}$ denotes the energy consumption per product of sector i in country j, and $\overline{F}_t(I - \overline{\Theta}_t)^{-1}\Psi^j_{i,t}$ denotes the indirect energy consumption per product according to Hendrickson et al. [45] and Druckman and Jackson [46].

2.3.2. Technology selecting

After filtering out the feasible low-carbon technologies, each county sector selects an imitating target from the set of feasible technologies. Following Wang et al. [36], we applied technology catch-up and transfer inertia to depict the technology transfer attractiveness between sectors and their feasible technologies via the Wilson spatial interaction formula.

Technology catch-up reflects the catch-up effect caused by technology gaps between countries. According to Wang et al. [36], the technology gap between nodes is the predominant driving force of technology diffusion in a network; the economic gap also plays an important role. This reflects the basic observed evidence in technology transfer that the institutes in middle and low developed regions prefer to cooperate with those in more developed regions [47], and cost reduction due to the technology gap is the main incentive for technology imitation, especially for the abatement technologies [48]. In this study, we have assumed the technology gap of sector i between country j and country k $\Delta e^{j,k}_{i,t}$ to be the ratio of their unitary energy costs and the economic gap $\Delta x^{j,k}_{i,t}$ to be the ratio of their GDP per capita [36].

$$Eg^{j,k}_{i,t} = \mu e^{\mu_0 \cdot \Delta c^{j,k}_{i,t} + \mu_0 \cdot \Delta x^{j,k}_{i,t}}, \quad \Delta c^{j,k}_{i,t} = \frac{c^j_{i,t}}{c^k_{i,t}}, \quad \Delta x^{j,k}_{i,t} = \frac{x^k_{i,t}}{x^j_{i,t}} \tag{14}$$

where $Eg^{j,k}_{i,t}$ is the technology catch-up intensity of sector i between country j and country k, and μ and μ_0 are the intensity parameters of technology catch-up.

Technology transfer inertia reflects the path dependence that is influenced by the cooperation relationships between sectors. Empirical evidence indicates that one's own experience with prior technology adoption plays an important role in technology adoption [49]. Assuming that the technology transfer frequency of sector i from country k and country j is $n_{i,t}^{j,k}$, the technology transfer inertia intensity $Ez_{i,t}^{j,k}$ can be given by:

$$Ez_{i,t}^{j,k} = \nu e^{\nu_0 n_{i,t}^{j,k}} \quad (15)$$

where ν and ν_0 are the intensity parameters of technology transfer inertia. Then, the technology transfer attractiveness can be given by:

$$E_{i,t}^{j,k} = Eg_{i,t}^{j,k} + Ez_{i,t}^{j,k} = \mu e^{\mu_0 \cdot \Delta c_{i,t}^{j,k} + \mu_0 \cdot \Delta X_{i,t}^{j,k}} + \nu e^{\nu_0 n_{i,t}^{j,k}} \quad (16)$$

The technology transfer attractiveness provides a probability basis for decision-making on the technology selection from the perspective of technology gap and cooperation intention. The probability that sector i in country j selects country k as its technology supplier can be given by:

$$TP_{i,t}^{j,k} = \frac{E_{i,t}^{j,k}}{\sum_{k}^{K} E_{i,t}^{j,k}} \quad (17)$$

2.3.3. Technology imitating and learning

When a sector has decided on its technology supplier (imitating target), it becomes a technology recipient (imitator). It will attain R&D acceleration, and the gap between its imitating target and its own will be decomposed into imitation and independent R&D parts by the transfer threshold. The imitation part can be accomplished through an accelerated R&D to catch up with its target in a shorter time with lower costs; however, the independent R&D part must be independently accomplished by the imitator itself for patent protection. That means the imitator will have a higher tech-shock variance to accelerate its process technology progress in the accelerated part. Equation (9) in Section 2.2 can be modified as:

$$\ln\left(a'_{k,j,i,t}\right) = \ln\left(a^*_{k,j,i,t,n}\right) + \varepsilon_{j,k,i,t,n}$$
$$\varepsilon_{j,k,i,t,n} \sim \begin{cases} N\left(0; s\rho_{k,t}^{j}\right) & \text{if } a^*_{k,j,i,t,n} > (1+W)\ a_{k,\tilde{j},i,\tau} \\ N\left(0; \rho_{k,t}^{j}\right) & \text{otherwise} \end{cases} \quad (18)$$

where sector i of country $\tilde{j}$ is the technology supplier that sector i of country j has selected in the process of technology selecting; $a^*_{k,j,i,t,n}$ is the intermediate input coefficient of sector i in country j for the product of sector k before one turn of technology shock; $a_{k,\tilde{j},i,\tau}$ is the relative intermediate input coefficient of the process technology of the supplier in step τ; $\tau$is the time when sector i of country j starts to imitate the process technology from sector i of country $\tilde{j}$, and s is the R&D acceleration for the imitator.

After decreasing the intermediate input coefficient to $(1+W)a_{k,\tilde{j},i,\tau}$ at an s times R&D speed, the imitator mush accomplish the remaining R&D part from $(1+W)a_{k,\tilde{j},i,\tau}$ to $a_{k,\tilde{j},i,\tau}$ independently, before starting a new turn of technology transfer.

Equation (18) shows that the independent R&D capability, which is determined by R&D investment and knowledge stock, affects the efficiency of technology learning and reflects the knowledge and investment barrier in technology transfer.

2.4. Data sources and parameter values

CIECIA-TD followed classifications of countries and economic sectors in CIECIA. The world was divided into 5 countries comprising China (CHN), India (IND), Japan (JPN), Russia (RUS), the United States (USA), and 5 groups comprising the European Union (EU), Other developed countries (ODC), High development countries (HDC), Medium development countries (MDC), and Low development countries (LDC). We merged 57 sectors in GTAP-8 into 12, comprising Agriculture (Agri), Food Processing (FdPro), Energy (Enrg), Metal and other Minerals (Mtl&Mn), Light Manufacturing (LghtMnfc), Chemical industry (ChemInd), Heavy Manufacturing (HvyMnfc), Construction (Const), Trade and Business Services (Trd&Busi), Transport and Communication (Trans&Comm), Insurance and Finance Services (Ins&Fin) and Other Services (OthServ).

The main economic data of CIECIA-TD, including gross output, value added, fixed capital, intermediate input, and energy consumption are obtained from GTAP-8. The carbon emissions and the carbon intensities of different types of energy of countries are obtained from the website of EIA (U.S. Energy Information Administration). The baseline parameters of knowledge stock are citied from Gu and Wang [33] and Wang et al. [33] in Table 1. The parameters for the process of technology transfer are cited from Wang et al. [36] and Gu and Wang [50] in Table 2 [36,50]. The values of the key parameters in Table 3 are cited from Jin [34] and Gu and Wang [32].

For the range of this study, the detailed outcomes of the baseline scenario and its calibration results will not be depicted. They can be obtained from Gu and Wang [32] and Wang et al. [33]. Due to the uncertainty of simulation outcomes caused by the stochastic mechanism of the technological innovation and transfer, every scenario in this study has been simulated 200 times, and the analyses of all scenarios in the following sections are based on the statistics of those simulations.

3. Simulations and results

3.1. Intellectual property regime scenarios

In this section, we have studied the economic and climatic impacts and carbon reductions of low-carbon technology transfer by scenario simulation using CIECIA-TD. Four technology transfer scenarios have been designed to study the climatic and economic impacts of changes of the global technological patent protection regime. The detailed parameter values are listed in Table 4. In Wang et al. [36], the values of R&D acceleration and technology transfer threshold are 2 and 0.2, respectively, reflecting the technology transfer and diffusion process between individuals under normal circumstances [36]. This indicates that the technology transfer threshold is 0.2 normally. However, the global intellectual property regime in the realm of low-carbon technology is quite uncertain. Although knowledge sharing and technology transfer have been included in many international technology-oriented agreements [51], the increasing new trade barriers and protectionism will negatively impact the international technology sharing and transfer. The recent USA–China trade negotiation has also focused on the international technology transfer.

For uncertainty of the global intellectual property regime for low-carbon technologies, we set the technology transfer threshold value in the four scenarios to 0.8, 0.5, 0.2, and 0. The transfer threshold in Scenario 3 reflects the normal technology transfer

Table 1
Related baseline parameter values of knowledge stock.

Country/Group	Output elasticity	R&D investment rate	Initial stock (billion USDollar)
CHN	0.015	0.0141	162.34
IND	0.01	0.005	24.30
JPN	0.045	0.0332	696.41
RUS	0.016	0.01	14.03
USA	0.043	0.0257	1727.99
EU	0.031	0.0165	1240.03
ODC	0.031	0.018	1569.56
HDC	0.016	0.0041	132.74
MDC	0.01	0.0014	58.38
LDC	0.009	0.0016	13.57

Table 2
Parameter values of the modules of process technology progress and technology transfer and diffusion.

Parameter	Value	Description
a^{ρ}	5.2298×10^{-3}	Parameter in Equation 11
b^{ρ}	1.0500×10^{-5}	Parameter in Equation 11
ω	0.75	Economic restriction parameter in Equation 12
μ	2	Intensity parameter of technology catch-up
μ_0	0.5	Intensity parameter of technology catch-up
ν	2	Intensity parameter of transfer inertia
ν_0	0.2	Intensity parameter of transfer inertia

mode in reality. In Scenarios 1 and 2, the intellectual property regime of countries is enhanced compared with the normal circumstances. In Scenario 4, the low-carbon technology can be fully shared around the world. This is an ideal circumstance, in which all countries are willing to share their advanced low-carbon technologies with other countries, and the low-carbon technologies become complete public products. The R&D acceleration in the four scenarios is 2; the other parameter values are the same as those for the baseline scenario. The technology transfer mechanism in these scenarios has been implemented since 2016.

According to Equation (12), the unitary energy cost depicts the technology level in technology transfer. Table 5 shows the average technology adoption lag among countries in the four scenarios during simulations. Comin and Hobijn found that the average adoption lag of advanced technology in the last two centuries was 45 years [52]. They also found that newer technologies have diffused much faster than have older technologies, with technologies that were invented ten years later than others being adopted, on average, 4.3 years sooner. Considering even faster technology diffusion in future, the average technology adoption lag in Scenario 3 (approximately 35 years) is close to this empirical evidence. This indicates that the value of the technology transfer threshold in Scenario 3 can reflect the technology transfer mode between countries under normal circumstances in reality.

Fig. 2 shows the share of technology transfer number between two specific countries during simulations in Scenarios 1 to 4. The outcomes indicate that developed countries, especially the USA, are the main advanced technology suppliers. In the four scenarios,

Table 4
Parameter setting of Scenarios 1 to 4.

Scenarios	R&D acceleration	Technology transfer threshold
Scenario 1	2	0.8
Scenario 2	2	0.5
Scenario 3	2	0.2
Scenario 4	2	0

Table 5
Average technology adoption lags in the four scenarios during simulations (year).

Scenario 1	Scenario 2	Scenario 3	Scenario 4
51.47	47.49	35.92	24.56

approximately 80% of the low-carbon technology transfers are from developed countries. The share of the developed country supplied technology transfer decreases slightly along with the decline of the technology transfer threshold, from 83 to 79%. The low-carbon technologies are transferred frequently between the developed countries. In Scenarios 3 and 4, more than 50% of the developed country–supplied technology transfer occurs between the developed countries. This is consistent with the observed reality that although developing countries had much stronger requirements on low-carbon technology sharing in past international climate negotiations, most technology transfer occurred between developed countries, rather than going to developing countries [44,53].

It is worth noting that the transfer share of low-carbon technologies to developed countries increases significantly along with the decline of the transfer threshold. In Scenario 1, only 23% of the technology transfer goes to the developed countries. In Scenario 4, when the technologies are completely shared, the share of the technology transfer to the developed countries increases to more than 65%. Table 6 shows the average numbers of technology transfer to countries in the four scenarios. From Scenario 3 to Scenario 4, the number of transfers to the developed countries increases significantly. The transfers to the USA increase from 5.1 in Scenario 3 to approximately 240 in Scenario 4, and those to the EU and the ODC increase by more than 300. The increase in the

Table 3
Parameter values of other key parameters.

Parameter	Value	Description
a	1.31	Total factor productivity of capital stock refresh in Equation 4
Φ	0.04	Output elasticity of capital stock investment in Equation 4
δ_Z	0.02	Depreciation rate of knowledge capital stock in Equation 5
δ_E	0.02	Depreciation rate of cumulative energy R&D investment in Equation 6
β	0.015	Discount rate of cumulative utility in Equation 8
ρ	0.2	Time preference of cumulative utility in Equation 8

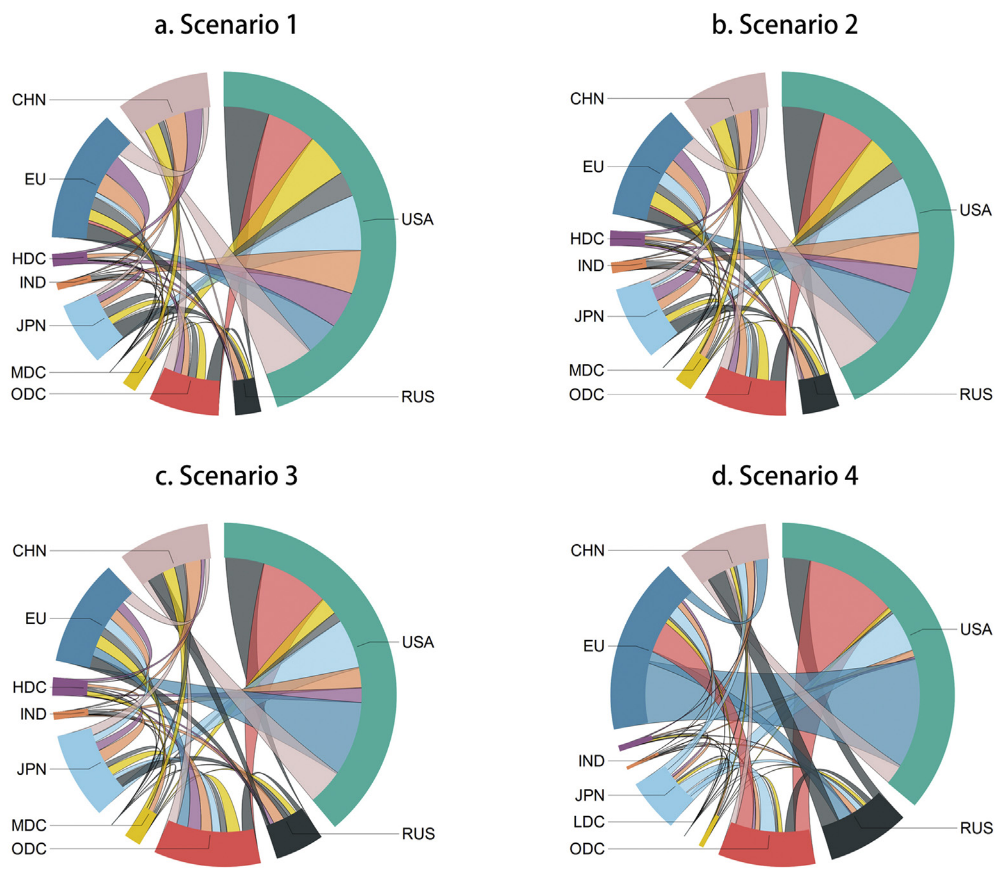

Fig. 2. Shares of total technology transfer number between countries in Scenarios 1 to 4 (%). The outer ring indicates the shares of countries as a technology supplier in technology transfer.

Table 6
Average numbers of technology transfer by country in the four scenarios.

	CHN	IND	JPN	RUS	USA	EU	ODC	HDC	MDC	LDC
Scenario 1	15.12	19.4	10.86	16.56	0.82	6.94	10.04	15.84	15.58	11.86
Scenario 2	20.04	25.04	18.52	21.18	0.96	17.06	14.46	16.78	20.9	14.72
Scenario 3	32.34	38.3	32.54	39.58	5.1	42.46	38.4	23.86	32.38	21.28
Scenario 4	149	93.42	207.98	187.04	239.12	394.28	359.98	33.6	63.9	42.76

Table 7
Average time spent on imitating and learning per technology transfer in the four scenarios (year).

CHN	IND	JPN	RUS	USA	EU	ODC	HDC	MDC	LDC
6.44	12.31	3.94	7.12	1.22	3.10	3.71	23.46	16.86	22.90

number of technology transfers to the developing countries is relatively steady from Scenarios 1 to 4.

This occurs mainly because of two reasons. First, as the technology gaps between the developed countries are much narrower than those from developed to developing countries (see Appendix II), the technology transfer threshold will significantly hinder the technology transfer between developed countries. Therefore, the transfer threshold decline will clearly increase the technology transfer frequency to developed countries, especially in Scenario 4, in which the technologies are completely shared. This result is also indicated in Fig. 2 and Table 6. Second, the R&D inputs, knowledge stocks, and process technology levels of developed countries are all much higher than those in developing countries (see Table 1). Therefore, it takes longer for a developing country to catch up with its learning target. This also increases the number of technology transfers to the developed countries. Table 7 shows that the average imitation time cost in a technology transfer for developed countries is below five years, whereas it takes the developing countries, especially the HDC and LDC, more than 20 years to catch up with their imitation targets.

Table 8
Global warming in 2100 from the pre-industrial level for Scenarios 1 to 4 (°C).

Scenarios	Mean	50% confidence interval	95% confidence interval
Scenario 1	3.0594	3.0526–3.0670	3.0284–3.0943
Scenario 2	2.9706	2.9652–2.9785	2.9371–2.9991
Scenario 3	2.8074	2.8027–2.8128	2.7918–2.8255
Scenario 4	2.4465	2.4435–2.4484	2.4371–2.4583

Table 8 shows the global warming in 2100 (°C) from the pre-industrial level in the four technology transfer scenarios. In the baseline scenario, the global mean surface temperature increases by approximately 3.20 °C in 2100. Along with the decline of

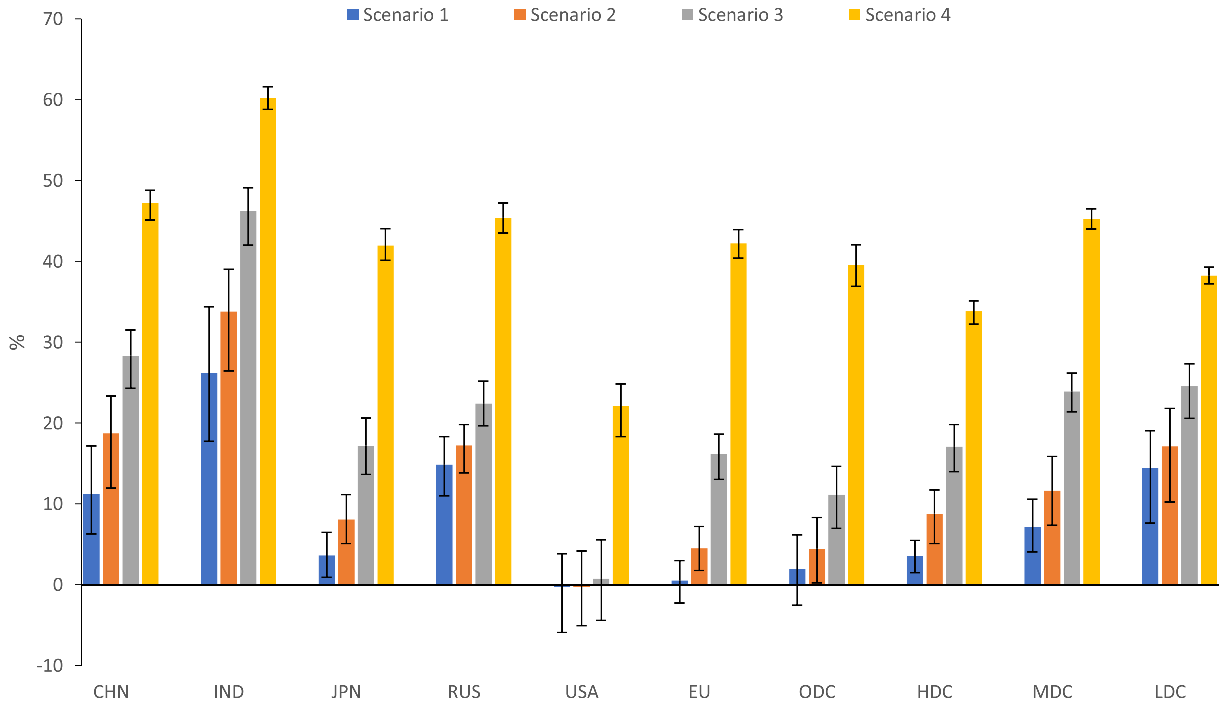

Fig. 3. Reductions of the cumulative carbon emissions by country between 2016 and 2100 compared to the baseline for Scenarios 1 to 4 (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

technology transfer threshold, the global warming decreases clearly. In Scenario 1, the global temperature rising in 2100 is 3.06 °C; in Scenario 3, the global warming decreases to 2.80 °C under the normal technology transfer circumstance; in Scenarios 4, the complete international technology sharing decrease the global warming to approximately 2.45 °C in 2100. However, it is still far from the 2 °C mitigation target in both the Copenhagen Consensus and the Paris Agreement.

Fig. 3 shows the cumulative carbon emission reductions by country for the four scenarios from 2016 to 2100 compared to the baseline. Along with the decline of technology transfer threshold, the cumulative carbon emissions of countries decrease significantly. In Scenario 1, the carbon reduction rate of India reaches 26%, followed by Russia and the LDC. The reduction rates of the ODC and USA are less than 2%. In Scenario 4, the carbon reduction rate of India reaches 60%, and the reduction rates of Japan, the EU and ODC all increase to greater than 40%. Compared with the carbon reductions of developed countries with those of developing countries, it is clear that developed countries are more sensitive to the decline of the technology transfer threshold. From Scenarios 1 to 4, the carbon emissions of developed countries decrease sharply, while the decreasing trends of the developing countries are relatively steadier. While the low-carbon technologies are fully shared, the carbon reductions of the developed countries increase significantly. The carbon reduction rate of the USA increases from less than 1% in Scenario 3 to more than 22% in Scenario 4. The reduction rates of the EU and ODC also increase from 16 and 11% in Scenarios 3 to 42 and 40% in Scenario 4, respectively; however, those of India and the LDC only increase by approximately 13% points.

This result is mainly due to the narrower technology gaps between the developed countries and their higher knowledge stocks. The transfer frequency of the low-carbon technologies to the developed countries increases significantly when the transfer threshold declines because of their narrower technology gaps. Developed countries can accomplish their technology learning in a short time (see Table 7) due to their higher knowledge stocks and R&D abilities, leading to more technology transfer in turn. While the technologies are completely shared, the increased frequency of technology transfer decreases the carbon emissions of the developed countries significantly. Therefore, the results in terms of technology transfer numbers and carbon reduction both indicate that the transfer threshold is the major barrier to low-carbon technology transfer to the developed countries.

By contrast, the carbon reductions of the developing countries under complete technology sharing are mainly limited by their lower knowledge capital stocks and R&D abilities, as their average technology learning time is much longer than is that of developed countries, which leads to fewer technology transfers. Several pieces of empirical evidence support this conclusion. Comin and Mestieri noted the existing evidence that the stock of knowledge and human capital played an important role in cross-country advanced technology adoption [49]. Kennedy and Basu defined the lack of R&D ability as the knowledge and investment barrier, and they also believed that the knowledge and investment barrier generated reluctance to adopt low-carbon technologies and negatively affected their widespread deployment in developing countries [44].

It is worth noting that the gap of the carbon reduction rates between the developed and developing countries in Scenario 4 is much smaller than those in Scenarios 1 to 3. That means the frequent technology transfer and exchange between the developed countries contribute to their long-term carbon reductions effectively. Therefore, in the future global carbon abatement cooperation, we should not limit the international low-carbon technological support to occurring from developed to developing countries. The low-carbon technology sharing between developed countries will also reduce significant carbon emissions, and deserves more attention.

Although the main technology transfer barrier to the developed countries is removed in Scenario 4, the developing countries still benefit more from the low-carbon technology transfer, in terms of both carbon reductions and economic development (we discuss the economic utility changes in Section 3.2). Therefore, encouraging technology sharing between developed countries does not mean that the technology transfer to developing countries is unimportant. Actually, the developing countries, especially China and India, contribute most of the carbon reduction in the four scenarios. Considering their limited transfer numbers, the carbon reduction potential of developing countries under technology transfer is significantly vast.

3.2. Policy mix with R&D improvement

In Scenarios 1 to 4, the 2 °C global warming target in the Copenhagen Accord and the Paris Agreement cannot be achieved solely by low-carbon technology transfer. The results indicate that although the developing countries achieve significant carbon reductions under low-carbon technology transfer and diffusion, they are still limited by their knowledge stock and R&D capability from reducing carbon emissions further.

For overcoming this barrier, we combined technology transfer with R&D investment improvement in this section, to improve the knowledge capital stocks and the basic R&D abilities of countries. Two scenarios were designed to enhance the R&D abilities of countries and improve the carbon reduction effects of technology transfer by improving R&D inputs. The R&D investment rates in these two scenarios are obtained by fitting the historical R&D expenditure data by logistic curve estimation according to Gu and Wang [32] to reflect the natural R&D input growth. Among them, the R&D investment rates of Russia, the MDC and LDC have overall downtrends due to their historical changes in the past twenty-five years. Direct energy R&D inputs are included in these two scenarios. In Scenario 5, following the current growth trends of the energy R&D expenditures, it is assumed that the energy R&D rates of all the countries reach 0.5% of the GDP by 2020 and then increase to 1% by 2100. In Scenario 6, for achieving the 2 °C target, the energy R&D rates reach 1.5% by 2020 and then increase to 2.1% by 2100. The overall R&D investment rates of countries are listed in Table 9. The values of the technology transfer threshold and R&D acceleration of these two scenarios are the same as those for Scenario 4, as well as the other parameter values. These R&D settings are also implemented since 2016.

Table 10 depicts the global warming in 2100 in the Scenarios 5 and 6. In Scenario 5, as the R&D inputs of countries increase, the global warming in 2010 declines to 2.17 °C. In Scenario 6, the direct energy R&D input rates of countries increase to 2.1% of the GDP in 2100, and the global warming in 2100 declines to approximate 1.98 °C, achieving the 2 °C mitigation target.

Fig. 4 depicts the reductions of the cumulative carbon emissions

Table 10
Global warming in 2100 from the pre-industrial level for Scenarios 5 and 6 (°C).

Scenarios	Mean	50% confidence interval	95% confidence interval
Scenario 5	2.1694	2.1662–2.1721	2.1607–2.1814
Scenario 6	1.9859	1.9827–1.9886	1.9792–1.9933

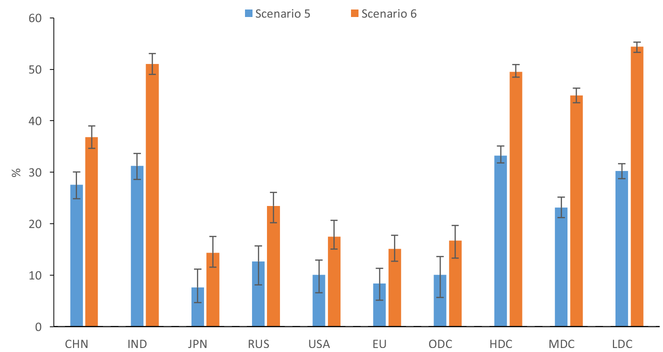

Fig. 4. Reductions of the cumulative carbon emissions by country between 2016 and 2100 compared to the Scenario 4 for Scenarios 5 and 6 (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

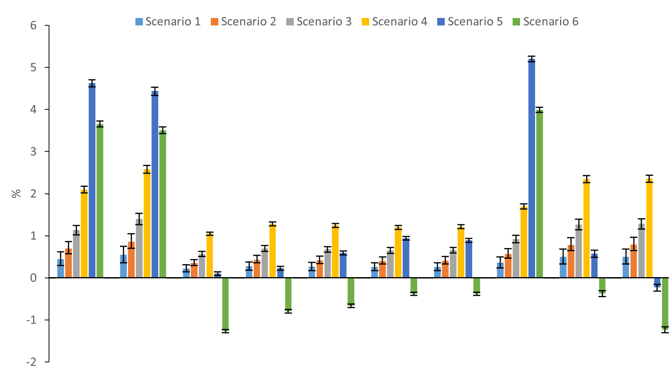

Fig. 5. Changes in cumulative utilities for the countries between 2016 and 2100 compared to the baseline for Scenarios 1 to 6 (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

Table 9
Overall R&D investment rates as a percentage of the GDP by country in Scenarios 5 and 6 (%).

Scenario	Year	CHN	IND	JPN	RUS	USA	EU	ODC	HDC	MDC	LDC
Scenario 5	2025	3.45	1.17	4.19	1.50	3.34	2.58	3.24	1.24	0.65	0.66
	2050	4.45	1.55	4.55	1.63	3.82	3.27	4.42	2.04	0.79	0.79
	2075	4.71	1.96	4.76	1.75	4.21	3.82	5.06	2.96	0.94	0.93
	2100	4.88	2.39	4.93	1.88	4.53	4.22	5.40	3.74	1.10	1.09
Scenario 6	2025	4.46	2.18	5.20	2.51	4.36	3.59	4.26	2.25	1.66	1.67
	2050	5.53	2.62	5.62	2.70	4.89	4.34	5.49	3.11	1.86	1.86
	2075	5.85	3.10	5.90	2.89	5.35	4.96	6.20	4.10	2.08	2.07
	2100	6.08	3.59	6.13	3.08	5.73	5.42	6.60	4.94	2.30	2.29

of countries and groups from Scenario 4 to Scenarios 5 and 6. In Scenario 5, the HDC reduce their cumulative carbon emissions by 33% from those in Scenario 4, followed by India, the LDC, and China, whose carbon reduction rates are all higher than 25%. In Scenario 6, the carbon reduction rates of the LDC and India reach 54 and 51%, respectively, and the carbon reductions of the HDC and MDC are both higher than 40%. This result indicates that the improvement of knowledge stock can significantly promote carbon reductions on the basis of technology transfer.

Although improvements of the R&D input rates of countries and groups from Scenario 4 to Scenarios 5 and 6 are similar, the developing countries are more sensitive to the improvement of R&D inputs and achieve higher carbon reduction rates. This result verifies the finding in Section 3.1 that the knowledge capital stock and R&D capability are the main barrier for the developing countries to achieve more carbon emissions from low-carbon technology transfer. In these two scenarios, the developing countries improve their knowledge stocks and R&D abilities by the additional energy R&D inputs, accelerate both their technology R&D and imitations, and benefit more from international technology transfer. In addition, the developed countries have generally industrialised with lower expected carbon emissions, which, to some extent, has a negative impact on their further carbon reductions.

Fig. 5 depicts the changes of the cumulative utilities of countries between 2016 and 2100 in Scenarios 1 to 6 compared to the baseline. In Scenarios 1 to 4, although the 2 °C mitigation target is not achieved, the cumulative utilities of countries increase along with the decline of the technology transfer threshold due to the climate welfare brought by the mitigation of global warming. According to Equation (2), climate mitigation will reduce the climate damage on production, and therefore improve the economy. The changes of the cumulative utilities differ between the developed and the developing countries. As the developing countries always have higher climate vulnerabilities [54–56], they obtain more economic benefits from climate welfare. In Scenario 4, the cumulative utilities of China, India, the MDC, and LDC all rise by more than two percent, and the rates of increase of the developed countries are all higher than one percent.

In Scenario 5, the utilities of China, India, and the HDC increase as they improve their R&D investment rates from those in Scenario 4, whereas the utilities of Russia, the MDC, and LDC decrease with the downtrends of their R&D input rates. Although the developed countries improve their R&D input rates in Scenarios 5, their utilities decrease compared with Scenario 4, even under increased economic benefit from the climate welfare.

That is mainly because of three reasons. First, developed countries have much higher knowledge capital stocks and, thus, are not as sensitive as are the developing countries to the improvement of R&D input. Second, compared with the developing countries, such as China and India, the improvements of R&D input of the developed countries are smaller, but the input rates of the additional energy R&D rates, which cannot improve production, are similar. Third, developing countries experience rapid economic growth after improving their R&D inputs. The increased economic development improves the capital attractiveness of the sectors in the developing countries and changes the global capital investment structure, leading to capital outflow in the sectors of the developed countries (see Appendix III). The outflowed capital enhances the economies of the developing countries, bringing fiercer market competition and shocks to the economic status of the developed countries in turn. Therefore, the utilities of the developed countries decrease compared with those in Scenario 4.

It is worth noting that the utilities of the least developed countries also decline in Scenario 5. That is because the R&D rates of these countries decrease in Scenario 5 according to their overall downtrends of R&D rates in the past 25 years.

In Scenario 6, along with the radical increase of the additional direct energy R&D inputs to 2.1% of the GDP in 2100 for the 2 °C target, the utilities of countries decline compared with Scenario 5. Those of the developed countries, Russia, MDC, and LDC are even lower than their baseline levels, as the price of carbon emission reduction and global warming mitigation. That is because of the excessive energy R&D input that leads to lower fixed capital investment.

4. Conclusions and discussion

This study improved and extended the climatic-economic integrated assessment model CIECIA by introducing a bottom-up process technology R&D and transfer mechanism to build CIECIA-TD to depict the global transfer of low-carbon technologies. This mechanism uses technology transfer threshold and R&D acceleration to depict the sharing degree of the advanced technologies and the absorbing ability of the imitator for the advanced technologies. On the basis of this model, the global warming mitigation, carbon reductions and economic impacts of low-carbon technology transfer were studied by scenario simulations. Based on this, we combined technology transfer with R&D improvements to study its climatic and economic impacts. The conclusions derived from the scenario simulations are listed below.

Technology transfer has significant carbon reduction and warming mitigation effects, as well as great potential to reduce carbon emissions in the future. While low-carbon technologies are completely shared between countries, technology transfer in Scenario 4 can reduce the global cumulative carbon emissions by approximately 40%. However, the 2 °C global warming mitigation target cannot be realized.

Developed countries with much higher knowledge capital stocks and low-carbon technology levels can learn and imitate the threshold-permitted part of advanced low-carbon technologies in a short time. Thus, developed countries show great carbon reduction potential through technology transfer when the low-carbon technologies are fully shared. In contrast, knowledge capital stock and R&D investment are more important for the developing countries in technology transfer.

Although the developing countries contribute most of the reductions and benefit more than do the developed countries, their lower knowledge stocks and R&D investments lead to a slower progression of technology learning and limited carbon reductions compared with those developed countries under complete technology sharing. This finding is consistent with Kennedy and Basu [44], who showed that the limited R&D investments in developing countries have negatively affected the widespread deployment of low-carbon technologies.

When combining the technology transfer with R&D improvements, the carbon emissions of countries decline further, especially in those developing countries whose carbon reductions in technology transfer are mainly limited by their lower R&D inputs and knowledge stocks. In Scenario 6, while the additional energy R&D input rates of countries increase to 2.1% of the GDP in 2100, the 2 °C target is realized by mitigating the global warming to 1.98 °C in 2100. However, most of the countries in these two scenarios suffer economic losses as the price of carbon emission reduction and global warming mitigation.

Although current appeals for advanced low-carbon technology sharing are mainly from developing countries, the results indicate that frequent technology transfers between developed countries achieves significant carbon reductions. Thus, in future international climate negotiation and cooperation, agreements on the international transfer and sharing of advanced low-carbon technologies should not be limited to those occurring from developed to developing countries, and the technology transfer between developed countries deserves more attention.

The economic core of CIECIA-TD is a multi-national-sectoral general equilibrium model, and its main data source is the national input–output tables. Thus, although the micro mechanism of technology transfer is introduced in this model, its concept of low-carbon technology is highly abstracted out from the craft technology at a macro level. The technology develops gradually and cannot reflect the emergence and spread of revolutionary technologies. The patent protection system is also relatively crude. Therefore, this model can only reflect the transfer trends of abstracted energy-saving technologies between sectors of countries and cannot depict the R&D and transfer of specialised technologies and other non-energy-saving ones, such as CCS. In addition, the R&D investment rates are also exogenous and cannot reflect the dynamic R&D incentive of firms while the intellectual property regime changes. We leave those for further study.

Credit author statement

Gaoxiang Gu: Conceptualization, Methodology, Software, Formal analysis, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Project administration, Funding acquisition; Zheng Wang: Conceptualization, Supervision; Leying Wu: Writing - Review & Editing.

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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.

Appendix I

The abbreviations and meanings of technical terms.

Table A1 shows the abbreviations and meanings of technical terms appearing in the Introduction, including the names of integrated assessment models and the technical terms of global climate change and mitigation.

Table A1
Abbreviation and meaning of technical terms

Abbreviations	Meanings
AEEI	Autonomous Energy Efficiency Improvement
AIM	The Asian-Pacific Integrated Model
CDM	The Clean Development Mechanism
CGE	Computable General Equilibrium model
C-GEM	Carbon-Generic Estuary Model
CIECIA	Capital Industrial Evolution and Climate Change Integrated Assessment model
CIECIA-TD	CIECIA model for Technology Diffusion
EPPA	The MIT Emissions Prediction and Policy Analysis model
IAM	Integrated assessment model
LBNL China End-Use Energy Model	Lawrence Berkeley National Lab China End-Use Energy Model
LEAP	The Low Emissions Analysis Platform
INDC/NDC	(Intended) Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
MERGE	Model for Evaluating Regional and Global Effects of GHG Reductions
REMIND	Regional Model of Investments and Development model
UNFCCC	United Nations Framework Convention on Climate Change
WITCH	World Induced Technical Change Hybrid model

Appendix II

The energy intensities of sectors in countries in 2007.

Table A2 shows the initial energy intensities of sectors in the model, on the basis of data sourced from GTAP-9 and EIA. In 2007, the energy intensities of sectors in the developing countries were generally much higher than were those in the developed countries. The energy intensities of the energy sectors (Enrg) of China and India were higher than 6 Mtoe/billion USD, whereas the intensities of the same sectors in Japan and the EU were all below 2 Mtoe/billion USD. The energy intensities of the chemical industries (ChemInd) in India and Russia were higher than 2 Mtoe/billion USD, whereas those in Japan, the USA, and the EU were below 1 Mtoe/billion USD. These results indicate that there was a huge low-carbon technology gap between the developed and developing countries.

Appendix IV

Prices and consumptions of products in 2100 in Scenarios 1 to 6 compared to the baseline.

Table A4 shows the average changes of global product consumption in 2100 in Scenarios 1–6 compared to the baseline. From Scenarios 1 to 4, along with the decline of global temperature and the improvement of the economy, the consumption of products increases steadily. In Scenario 5, although the utilities of the developed countries, Russia, the MDC, and LDC decrease compared to Scenario 4, the economic growth in China, India, and the HDC raises the global consumption by approximately 10% from the baseline level. In Scenario 6, as all the countries suffer from excessive direct energy R&D, the global consumption of products decreases.

Table A2
Energy intensities of sectors in countries in 2007 (Mtoe/Billion US Dollars)

Sectors	CHN	IND	JPN	RUS	USA	EU	XOECD	HD	MD	LD
Agri	0.2382	0.4304	0.1637	0.2442	0.1931	0.1299	0.186	0.2082	0.2054	0.0703
FdPro	0.2055	0.1723	0.0606	0.5365	0.1676	0.0895	0.1053	0.1658	0.1731	0.0654
Enrg	6.3935	6.2473	1.874	2.8015	4.0486	1.9856	2.1679	1.616	2.4764	0.8417
Mtl&Mn	1.6478	0.9252	0.4001	1.7315	0.3202	0.2492	0.4444	0.8052	0.7221	1.1558
LghtMnfc	0.553	0.4117	0.116	1.3112	0.1868	0.1263	0.2261	0.3472	0.2845	0.2206
ChemInd	1.9276	2.0227	0.6904	8.7364	0.7157	0.4032	1.1924	1.2539	1.2007	2.5712
HvyMnfc	0.2147	0.3286	0.0502	0.4076	0.06	0.0405	0.058	0.1438	0.246	0.622
Const	0.2563	0.0172	0.0211	0.0779	0.0059	0.0101	0.018	0.0402	0.0754	0.0357
Trd&Busi	0.1508	0.0949	0.0353	0.0791	0.0533	0.0284	0.0518	0.0846	0.144	0.0689
Trans&Comm	0.8829	0.6579	0.3109	1.6031	0.942	0.5479	0.6253	0.8354	1.4559	1.1478
Ins&Fin	0.0617	0.0971	0.0089	0.0635	0.0155	0.0164	0.0143	0.0446	0.0612	0.0534
OthServ	0.1356	0.0057	0.0421	0.1766	0.0452	0.0304	0.0361	0.0656	0.1052	0.1122

Appendix III

The global investment shares of countries in baseline and Scenarios 1 to 6.

Table A3 shows the average global investment shares of countries in the seven scenarios. The percentage share of global investment indicates the economic status of a country in the system of international capital flow. Along with the decrease of global surface temperature, the economic improvements of the developing countries are higher than are those of the developed countries, leading to a higher percentage of investment shares. The changes in capital investment influence the economic growth in turn, and the percentage of investment shares of the developed countries decreases further. In Scenarios 5 and 6, because of the downtrends of R&D investment rates, the percentage investment shares of Russia, the MDC, and LDC also decline with those of the developed countries.

Table A4
Average changes of global product consumptions in 2100 compared to the baseline for Scenarios 1 to 6 (%).

Products	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Agri	1.52	2.37	3.90	7.04	10.42	9.72
FdPro	1.69	2.63	4.33	7.84	10.55	8.96
Enrg	1.81	2.82	4.65	8.44	10.66	8.40
Mtl&Mn	1.69	2.64	4.35	7.87	10.55	8.92
LghtMnfc	1.65	2.58	4.24	7.68	10.54	9.14
ChemInd	1.74	2.71	4.46	8.08	10.55	8.65
HvyMnfc	1.64	2.56	4.21	7.62	10.54	9.21
Const	1.60	2.50	4.12	7.45	10.52	9.38
Trd&Busi	1.71	2.67	4.39	7.96	10.50	8.71
Trans&Comm	1.74	2.71	4.46	8.09	10.51	8.58
Ins&Fin	1.79	2.78	4.58	8.31	10.46	8.23
OthServ	1.70	2.64	4.35	7.89	10.50	8.82

Table A3
Average global investment shares of countries in the baseline and Scenarios 1 to 6 (%)

Scenarios	CHN	IND	JPN	RUS	USA	EU	XOECD	HD	MD	LD
Baseline	23.39	10.52	2.09	2.45	14.12	11.82	4.24	14.09	11.66	5.63
Scenario 1	23.41	10.55	2.08	2.44	14.09	11.79	4.23	14.08	11.68	5.64
Scenario 2	23.42	10.57	2.08	2.44	14.07	11.78	4.23	14.08	11.70	5.64
Scenario 3	23.44	10.59	2.07	2.43	14.04	11.75	4.22	14.08	11.72	5.65
Scenario 4	23.48	10.65	2.06	2.42	13.98	11.70	4.20	14.07	11.77	5.67
Scenario 5	24.31	10.78	2.00	2.32	13.62	11.56	4.19	14.85	11.11	5.26
Scenario 6	24.34	10.79	2.00	2.32	13.60	11.54	4.19	14.83	11.13	5.26

Table A5 shows the average changes of product prices in 2100 compared to the baseline for Scenarios 1–6. It is worth noting that the prices of the energy product increase along with the decline of the technology transfer threshold in Scenarios 1 to 4. This result is consistent with the conclusion that the decline in energy intensity caused by technological innovations in the production process will lead to a decline in energy prices and, consequently, may cause excessive energy consumption [57]. However, the price of the energy product increases slightly, and its influence on the carbon reduction is negligible. In Scenario 6, the product prices of energy-intensive sectors such as the energy (Enrg) and chemical industry (ChemInd) increase. That is mainly because the excessive energy R&D rate affects the fixed capital investment negatively. Thus, the product prices of other capital-intensive sectors, such as the transport and communication services (Trans&Comm) and the insurance and finance services (Ins&Fin), also increase in Scenario 6.

Table A5
Average changes of product prices in 2100 compared to the baseline for Scenarios 1 to 6 (%).

Products	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Agri	0.18	0.27	0.44	0.80	0.09	−0.81
FdPro	0.01	0.02	0.03	0.06	−0.03	−0.12
Enrg	−0.11	−0.17	−0.28	−0.50	−0.13	0.39
Mtl&Mn	0.01	0.01	0.01	0.03	−0.03	−0.09
LghtMnfc	0.05	0.07	0.11	0.20	−0.02	−0.28
ChemInd	−0.04	−0.06	−0.09	−0.17	−0.03	0.16
HvyMnfc	0.06	0.09	0.14	0.26	−0.02	−0.35
Const	0.09	0.14	0.23	0.42	0.00	−0.51
Trd&Busi	−0.01	−0.02	−0.03	−0.06	0.02	0.10
Trans&Comm	−0.04	−0.06	−0.10	−0.17	0.01	0.22
Ins&Fin	−0.09	−0.13	−0.21	−0.38	0.05	0.55
OthServ	0.00	0.00	0.01	0.01	0.01	0.01

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