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Research on global carbon abatement driven by R&D investment in the context of INDCs

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A B S T R A C T

The intended nationally determined contributions were adopted as the national plans for addressing the climate change challenge after 2020, aiming at limiting global warming to 2 or 1.5 °C. In this context, energy-saving R&D has become an important way for reducing GHG emissions. This study used a climate-economy integrated assessment model to study the carbon reduction and climate mitigation effects of R&D investment by scenario simulation. The results show that most of the major carbon emitters cannot achieve their INDC targets by continuing their current R&D growth trends. Unless the R&D investment rates of countries increase to radically high levels, global warming by 2100 cannot be controlled to below 2 or 1.5 °C even when the major carbon emitters have approached or achieved their INDC targets. Low-carbon technology transfer will obviously reduce the carbon emissions of developing countries, but cannot achieve the 2 °C target. Considering the actual R&D capabilities of countries and the economic loss under excessive R&D input, raising R&D rates to approximately 4 or 5 percent and combining them with technology transfer and production damage measures will be a more realistic approach.

1. Introduction

Global climate change and mitigation have been heavily researched and remain among the most challenging issues recently being widely and intensively discussed around the world [1]. The emission of greenhouse gases by the heavy use of fossil fuels is one of the main recognized causes of global climate change, leading to global warming [2]. Since industrialization, the global concentrations of carbon dioxide, methane and nitrous oxide have significantly increased to levels far higher than those observed before industrialization. Since the foundation of the United Nations Framework Convention on Climate Change (UNFCCC), after more than 20 years of negotiations and discussion, the urgency and necessity for immediate global mitigation of greenhouse gases has been agreed to and accepted by most of the countries in the world.

In the Paris Agreement, which was adopted under the United Nations Framework Convention on Climate Change in December 2015, the intended nationally determined contributions (INDCs) were welcomed as the greenhouse gas reduction plans of countries to hold the targets of “the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” in order to prevent dangerous interference with climate system and ensure economic development [3-5]. To date, more than 190 countries/regions, which emitted more than 95 percent of world's greenhouse gases in 2012, have submitted their INDCs. That means global climate protection has finally come into the specific implementation period. Therefore, controlling and reducing global GHG emissions, especially carbon dioxide, to mitigate global climate change in the context of the INDCs will play a significant role in the future development of the global economy and society.

The main source of GHG emissions is industrial production, especially the energy sectors, using fossil fuels that generate carbon emissions [6]. Therefore, energy-saving technology is important for reducing carbon emissions [7]. Promoting the research and application of energy-saving technologies is an effective way to mitigate industrial greenhouse gas emissions. Although some scientists believe that the decline in energy intensity caused by technological innovations in the production process will lead to a decline in

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energy prices and consequently may cause excessive energy consumption [8], proposing increased research and development (R&D) spending to improve energy-saving technologies for reducing the demand for energy has been widely considered as an important solution to the climate change problem for a long time [9-10].

The carbon mitigation effect of R&D policy has been widely discussed, both on global and on regional scales. Many of those studies are based on methods such as statistics, measurement and data analysis, especially on the regional and national level [11-14]. Those methods focus on the existing data and the statistical relationships among the factors, and thus cannot reflect the dynamic relations among the economy, technological progress, energy use, and carbon emissions.

To study the impacts of R&D on carbon emissions and the world economy, and to address global warming in the context of the INDCs, we should use a model that reflects the interactions among economic growth, carbon emissions, and climate change under the background of global warming. At present, the integrated assessment models (IAMs) have been widely used to solve those problems. Nordhaus analyzed the impact of induced innovation on carbon intensity using R&DICE models [15]. Popp studied the impact of R&D policies with or without other climate policies such as a carbon tax by using a modified version of the DICE model called ENTICE [9,16]. Bosetti et al. used the WITCH model to obtain optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations [17]. Nemet and Baker combined an expert elicitation and a bottom-up model to study the mitigation effects of R&D and compare it with demand side support [18]. Bosetti et al. assessed the impact of the future cost of key low-carbon technologies by comparing the outcomes from GCAM, MARKAL_US, and WITCH [19]. Marangoni et al. employed WITCH to solve the optimal R&D portfolio in four key clean energy technologies [20]. Although having achieved many significant achievements, those IAMs still have some shortcomings in their depictions of technological progress.

Traditionally, the concept of energy-saving or low-carbon technology refers to those directly reducing the demands of energy products or carbon emissions during production. In this perspective, R&D for energy-saving technologies (energy R&D) is distinct from the other forms of R&D [9]. Only R&D for reducing energy costs or for improving carbon-free energy technology reduces the carbon emissions in the production process. However, from a broad perspective, especially from the perspective of input-output analysis, the energy-saving technology should include the technology that reduces the demand for non-energy intermediate products per output, because the production of intermediate input also consumes energy, and the gross carbon intensity decreases along with the decline of intermediate demand, no matter whether it is carbon energy or not. The direct energy-saving technology is contained in this broad concept. We called this intermediate input-saving technology improvement “process technological progress”. To date, except for some CGE models, few IAMs include the broad concept of energy-saving technology. The current IAMs, especially those bottom-up models usually including detailed specified energy systems, widely adopted and implemented the learning-by-doing or learning curve approaches in which the costs of various technologies or energy/carbon intensities decrease with experience or cumulative investments [16,21-23], and cannot reflect the broad energy-saving technology.

Further, this situation indicates another major shortcoming of the current IAMs: an over-simplified macro-economic module that cannot depict the input-output relations among sectors. Despite those bottom-up models that typically did not include detailed modelling of the overall macro-economy, many up-down IAMs also lacked detailed input-output structure in their economic modules. Among them, the well-known DICE simplified the world economy as a whole [24]. RICE and MERGE divided the global economy into country levels, but did not contain industrial structures and ignored the economic relations among countries [25-26]. The same problems existed in many extended or modified versions of DICE and RICE, such as DICE-2007, RICE-2010, and DSICE [27-29]. MRICES, an advanced version of RICE, designed an international economic interacting mechanism using a GDP-spillover model, but this model still cannot accurately depict the national economic relations in the context of global integration [30]. Compared with its former versions, the macro-economic structure of REMIND-v1.6 used a nested production function and contained different kinds of energies and their trade mechanisms. However, except energy, the other goods were composited as one product [23,31].

For overcoming the flaws of the models mentioned above, we adopted a new climate-economy IAM, named the Capital, Industrial Evolution and Climate change Integrated Assessment model (CIECIA for short) [32] to study the mitigation effects of R&D policies in the context of INDCs. The economic core of CIECIA is a multi-national-sectoral general equilibrium model that is modified and extended on the basis of Jin [33]. It contains a detailed national input-output structure. Based on the economic model, the broad concept of energy R&D and low-carbon technology is realized by employing a stochastic technological progress mechanism from Lorentz and Savona that is driven by knowledge stocks [9,34-35]. This mechanism models each sector in the countries as a firm with intermediate input coefficients. The intermediate input coefficient is stochastically shocked in each step. The sectors accept a new set of intermediate input coefficients if its unitary cost is lower than the former. This mechanism reflects the self-selection and adoption mechanism of process technology for specific sectors. Based on this IAM, global warming, economic growth, and carbon emissions of countries between 2007 and 2100 in different R&D scenarios compared with those in the baseline are simulated. The feasibility and effectiveness of R&D policies for the INDCs and the 2 and 1.5 °C global warming control targets are also discussed. In addition, the climate-economy effects of technology transfer and diffusion are studied by adopting an individual-imitation based technology diffusion mode in this IAM.

2. Model and data sources

CIECIA mainly comprises a multi-national-sectoral general equilibrium model as its economic core, a global carbon cycle model as its climate module and an R&D driven stochastic process technological progress mechanism reflecting the decline of intermediate demand in the production process [32].

The multi-national-sectoral general equilibrium is the economic core of this IAM. General equilibrium theory has been widely discussed and used in many fields, including economic policy making, globalization, international trade, and capital flow, to reflect an economy-wide equilibrium of the interactions of all prices with the supply and demand for all commodities among all sectors in all countries [36]. As such, general equilibrium models have had a significant impact on the applications of economics in the real world.

However, the economic basis of the general equilibrium has long been controversial. The existence of an equilibrium point is based on the assumptions that may defy common sense and ordinary experience, lack empirical basis, or have no economic meaning. Moreover, some of those assumptions or conditions were designed for mathematical convenience or computability. For example, quantities and prices are assumed to take on any real number values, all market participants have perfect information, there are flaws in theory basis of technology change and adoption, all the markets have to clear, and fundamental uncertainty neglected [37-41].

In this study, to research the climate-economy effects of R&D investment, we need to identify the economic relations and interactions among the various economic sectors of different countries, and, at the same time, ensure the computability of the model. Therefore, despite all shortages of the general equilibrium theory, we choose use this widely-used economic modelling method, and perform our research in a global economic equilibrium context. Moreover, to overcome the typical flaws of the general equilibrium model regarding uncertainty and technology progress, a process technological progress mechanism based on a logarithmic stochastic shock is introduced in CIECIA.

The general equilibrium model in CIECIA is modified and developed from Jin [33]. It is assumed that capital and commodities move freely among countries and sectors, without any investment or trade barriers. Labour also moves freely among the sectors of the same country, which means its wage rate in one step is uniform across sectors. The discount rates of countries are exogenous and uniform, and each sector uses identical output elasticity of its fixed capital stock. Moreover, each country uses identical technology that completely contributed to forming effective labour in one step. Meanwhile, the market clear assumptions for equilibrium of Jin are followed: the elasticity of substitution of intermediate goods is unitary, consumers have logarithmic preferences, and the fixed capital accumulation is log-linear [33].

In this IAM, the world is divided into countries denoted by j; the economic system of each country is composed of sectors denoted by i.

2.1. Production

A two-layered production function comprises the Leontief and the Cobb-Douglas is employed to depict the production of sectors and to represent the relationships among labour, capital, value added and gross output. The sectoral gross output is composed of value added and intermediate inputs, and the value added is formed by labour, fixed capital stock and knowledge capital stock.

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

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

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

where $X_{i,t}^{j} p_{i,t}$ 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; $K_{i,t}^{j}$ 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 knowledge capital stock, $\beta_{j,t}^{Z}$ is the output elasticity of knowledge stock; $p_{k,t}$ is the product price, and $\Omega_{i,j,t}$ is the damage factor for rising temperature.

The wage rate equals the marginal output of labour. Because of the full mobility of workers in one country, there is a unique wage rate across sectors in one country.

$$w_{i,t}^{j} = \frac{\partial X_{i,t}^{j}}{\partial L_{i,t}^{j}} p_{i,t} = (1-\alpha_i)\frac{X_{i,t}^{j}}{L_{i,t}^{j}} p_{i,t} \tag{4}$$

Fixed capital stock is accumulated under the Cobb-Douglas form [33,42]. The knowledge stock is accumulated under the Perpetual Inventory Method. Here, we distinguish the direct energy R&D expenditure for improving energy efficiency, exploring renewable energy sources, or researching nuclear, power or other storage technologies from the overall R&D investment. The energy R&D affects the process technological progress of the energy sector, but will not be counted as knowledge stock, and will not have an effect on production.

$$K_{i,t+1}^{j} = a\left(Ik_{i,t}^{j}\right)^{\varphi}\left(K_{i,t}^{j}\right)^{1-\varphi} \tag{5}$$

$$Z_{t+1}^{j} = (1-\delta_Z)Z_t^j + Iz_t^j \tag{6}$$

$$\sum\nolimits_j^J Iz_t^j + \sum\nolimits_j^J Ie_t^j + \sum\nolimits_j^J \sum\nolimits_i^I Ik_{i,t}^{j} = I_t^g \tag{7}$$

where $Ik_{i,t}^{j}$ is the fixed capital investment, Iz_t^j is the R&D input, Ie_t^j is the direct energy R&D input, I_t^g is the global investment. The marginal output of the fixed capital investment that indicates the inverse of the price of capital can be obtained by the partial derivatives of $Ik_{i,t}^{j}$.

$$q_{i,t}^{j} = 1\bigg/\frac{\partial K_{i,t+1}^{j}}{\partial Ik_{i,t}^{j}} = \frac{1}{a\varphi}\left(\frac{Ik_{i,t}^{j}}{K_{i,t}^{j}}\right)^{1-\varphi} \tag{8}$$

The market clearing equation of price in each sector is given by Ref. [33]:

$$p_{i,t} = \frac{\gamma_i}{X_{i,t}^{g}} X_t^g \tag{9}$$

where γ_i indicates the global output share of good i. The global associated price index is normalized to 1.

$$\overline{p}_t = \prod_i^I \left(p_{i,t}\right)^{\gamma_i} = 1 \tag{10}$$

In addition, the Keynes-Ramsey utility is adopted to reflect economic power [30].

$$U^j(T) = \sum_{t=1}^{T} (\beta+1)^{-t} Pop_t^j \frac{\left(C_t^j / Pop_t^j\right)^{1-\rho}}{1-\rho} \tag{11}$$

where $U^j(T)$ is the cumulative utility of country j by step T; C_t^j is the consumption; Pop_t^j is the population; β is the discount rate; and ρ is the time preference of consumers.

2.2. Process technological progress

A mechanism of stochastic logarithmic shock is adopted in CIECIA [34]. In this mechanism, the intermediate input coefficient $a_{k,i,j,t}$ is randomly shocked in a logarithmic form for N times in one step, to depict the decrease of intermediate demands in the production.

$$\ln\left(a'_{k,j,i,t}\right) = \ln\left(a^*_{k,j,i,t,n}\right) + \varepsilon_{j,k,i,t,n}, \quad \varepsilon_{j,k,i,t,n} \sim N\left(0; \rho^j_{k,t}\right) \tag{12}$$

where $\varepsilon_{j,k,i,t,n}$ is the stochastic shock; n denotes the turn number of tech-shock; $a^*_{k,j,i,t,n}$ is the intermediate demand coefficient of product k after n turns.

After the one turn, a new set of intermediate demand coefficient $(a'_{1,j,i,t}, \ldots, a'_{k,j,i,t}, \ldots, a'_{I,j,i,t})$ is generated. The new set of coefficients will be accepted to replace the former one if the potential unitary cost is lower; otherwise, this new set will be abandoned.

$$\left(a^*_{1,j,i,t,n}, \ldots, a^*_{I,j,i,t,n}\right) = \begin{cases} \left(a'_{1,j,i,t}, \ldots, a'_{I,j,i,t}\right) & \text{if } \sum_k^J a'_{k,j,i,t} p_{i,t} < \sum_k^J a^*_{k,j,i,t,n-1} p_{i,t} \\ \left(a^*_{1,j,i,t,n-1}, \ldots, a^*_{I,j,i,t,n-1}\right) & \text{otherwise} \end{cases} \tag{13}$$

After N turns, the intermediate demand coefficients for the next step can be obtained by:

$$\left(a_{1,j,i,t+1}, \ldots, a_{I,j,i,t+1}\right) = \left(a^*_{1,j,i,t,N}, \ldots, a^*_{I,j,i,t,N}\right) \tag{14}$$

Equation (12) shows that the variance $\rho^j_{k,t}$ of stochastic shock determines the pace of process technological progress. In this study, it is assumed that the value of $\rho^j_{k,t}$ is determined by the ratio of knowledge stock in the total capital. In this study, for distinguishing direct energy R&D input from the overall one, the cumulative energy R&D expenditure affects the variance of stochastic shock for the intermediate input coefficient of energy product (intermediate energy input coefficient). Therefore, the function of the stochastic shocking variance can be given by

$$\rho^j_{k,t} = \begin{cases} a^\rho \dfrac{Z^j_t + \sum\limits_{\tau=0}^{t} (1-\delta_E)^{t-\tau} Ie^j_\tau}{Z^j_t + \sum\limits_{\tau=0}^{t} (1-\delta_E)^{t-\tau} Ie^j_\tau + K^j_t} + b^\rho + c^\rho_{j,t} & \text{if } k = Enrg \\ a^\rho \dfrac{Z^j_t}{Z^j_t + K^j_t} + b^\rho + c^\rho_{j,t} & \text{otherwise} \end{cases} \tag{15}$$

where a^ρ and b^ρ are parameters, and $c^\rho_{j,t}$ is an adjustment to the rate of process technological progress.

This process, in which the sector adopts the technology that lowers its cost and abandons the others, depicts a sector's self-selection of technology, and reflects the evolution mode that was recognized by Nelson and Winter [43], that is, from the micro-cosmic point, the technological progress is the result of selection of enterprise for profit, rather than being just a slow, incremental process. This mechanism reflects the randomness of and autonomous nature of technological progress and adoption, and is far closer to reality. It is worth noting that in the model, the determining factor for technology adoption is its potential unitary cost. That means in extreme situations, the gross carbon intensity of a new adopted technology will be higher than the former. However, in the long run, the gross carbon intensity will definitely decline along with the decrease of intermediate demands, which will be discussed in the next section. In addition, this indiscriminate process technological progress avoids both the market failure that firms have no incentive to develop low-carbon technology and excessive energy consumption that is caused by too fast direct energy-saving technological progress [8-9].

2.3. Carbon emission and the climate model

The energy consumption in the production process is supplied by the energy sector.

$$E^j_{i,t} = \tau^E_{i,j} a_{E,j,i,t} X^j_{i,t} \tag{16}$$

where $a_{E,j,i,t}$ is the energy demand coefficient of sector i in country j; $\tau^E_{i,j}$ is the energy intensity of energy products. The energy products are divided into coal, oil, gas and electricity, and the energy structures of countries and their change trends are exogenous. The gross carbon emission is determined by energy consumption in the production process, $E^j_{i,t}$, the final energy consumption, $E^C_{j,t}$, energy structure $\kappa_{e,i,t}$, and carbon emissions intensity, $\tau^C_{j,e}$, of special fossil fuel.

$$QP^j_t = \sum_e^E \tau^C_{j,e} \kappa_{e,j,t} \left(E^C_{j,t} + \sum_i^I E^j_{i,t}\right) \tag{17}$$

The energy structure was obtained by fitting the historical energy data from the EIA [44] and extrapolating exogenously. In addition, CIECIA also considers the carbon emissions from land use change. Therefore, the global carbon emission in step t is given by

$$Q_t = \sum_j^J QP^j_t + QL_{t0}(1-\gamma_{le})^t \tag{18}$$

where γ_{le} is the yearly decay rates of carbon emissions from land use change.

The global carbon emissions lead to rising atmospheric temperature, and inflict damage on the economy in turn. The climate damage function in CIECIA follows Nordhaus and Yang, and Pizer [25,45], and can be given by

$$\Omega_{i,j,t} = \frac{1 - b_{1,j}}{1 + (D_{0,j}/9) T_t^2} \tag{19}$$

where $b_{1,j}$ is the production damage factor in country j; $D_{0,j}$ is the loss ratio of the GDP when temperature rises 3 °C; and T_t is the temperature rising in step t.

A carbon-cycle model developed by Svirezhev et al. is adopted in CIECIA [46]. This model divided the carbon-cycle process into the terrestrial carbon cycle, the ocean carbon cycle and the atmospheric carbon cycle. Among them, the terrestrial carbon is shared by two compartments: the biota (vegetation) and the pedosphere (soils). Svirezhev carbon-cycle model which contains a terrestrial ecosystem turns out to be superior to the solo-reservoir and three-reservoir models of DICE/RICE in terms of a much more detailed model mechanism and more accurate modelling performance.

$$\Psi_t = \Psi_{t-1} + Q_t - \Delta V_t - \Delta So_t - \Delta O_t \tag{20}$$

where Ψ_t is the atmospheric carbon content, ΔV_t is the net change of the amount of carbon in vegetation; ΔSo_t is the net change of the amount of carbon in soils; ΔO_t is the net change of the carbon content in the ocean. For a detailed structure of this model, see Svirezhev et al. [46].

2.4. Data sources

The economic data, including gross output, value added, fixed capital, intermediate inputs, and energy consumption are mainly 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. The parameter values of the climate module, including damage function and carbon-cycle model are obtained from to Nordhaus and Yang, Pizer, and Svirezhev et al. [25,45-46]. Populations of countries and their growth rates are obtained from World Population Prospects [47], and the population structures are obtained from the World Bank [48]. The savings rates of countries are cited from Ma and Yi [49]. The parameters of knowledge stock in baseline are citied from Wang et al. in Table 1 [30], and the other important parameters are listed in Table 2.

The values of a^ρ and b^ρ in Equation (15) are 5.2298×10^{-3} and 1.0499×10^{-4} respectively. Table 3 shows the values of $c^\rho_{j,t}$. In the regression analysis of Eq. (25), R^2 is 0.8740, and the t statistics of these two parameters are −2.89 and 7.75 respectively. The hypothesis of Equation (15) passes the test.

For simplification, CIECIA merged 57 sectors in GTAP-8 into 12, comprising Agriculture (Agri for short), 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 world was divided into 10 countries/regions, comprising China (CHN, for short), the United States (USA), Japan (JPN), the European Union (EU), Russia (RUS), India (IND), Other developed countries (ODC), High development countries (HDC), Medium development countries (MDC), and Low development countries (LDC), as the same as Wang et al. [30].

Table 1
Related parameter values of knowledge stock in baseline.

	Output elasticity	R&D investment rate	Initial stock (billion USDollar)
CHN	0.015	0.0141	162.34
USA	0.043	0.0257	1727.99
JPN	0.045	0.0332	696.41
EU	0.031	0.0165	1240.03
IND	0.01	0.005	24.30
RUS	0.016	0.01	14.03
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
Other important parameters.

Parameter	Value	Description	Source
φ	0.04	Output elasticity of investment	Jin [33]
θ	1	Constant substitution elasticity in compound functions of consumption, investment and price	Jin [33]
ρ	0.198	Time preference	Wang et al. [30]
β	0.015	Discounting rate	Buchner and Carraro [50]; Wang et al. [30]
QL_{t0}	1.5202	Carbon emissions from land use in 2007	Nordhaus and Yang [25]
γ_{le}	0.02	Yearly decay rate of carbon emissions of land use	Nordhaus and Yang [25]

3. Simulations and results

Based on CIECIA, the economic growth, energy use and carbon emission, as well as global climate change between 2007 and 2100 were simulated. First, to verify the validity of the model, the outcomes in the baseline scenario, including GDP, current account balance, energy use and the carbon emissions of countries between 2007 and 2012 are calibrated using regression analysis, a Z-test, and ANOVA. The real data of GDP, energy use and carbon emission are from the EIA, and the current account balance are from the IMF [51]. Table 4 shows that the correlation coefficients of the regression analysis are all larger than 0.9, and these *P*-values are all close to 0. The outcomes of the Z-test and ANOVA also show that there is no significant difference between the simulation outcomes and the historical data. The calibrating results indicate that the simulation outcomes of the baseline scenario are close to the real world, and can exactly reflect reality. For the range of this study, the detailed outcomes of the baseline of CIECIA will not be depicted. They can be obtained from Wang et al. [32].

In this section, as per the baseline, four R&D scenarios are designed to increase the R&D inputs of countries toward accelerating the process technological progress according to Equation (15). The historical trends of the national R&D investments are rather complex. Generally, the R&D investment rates of developed countries fluctuated in an upward trend between 2000 and 2014. According to the IMF [51] and the World Bank [52], the R&D investing rate of the USA from 2000 to 2014 fluctuated between 2.5 and 2.7 percent of the GDP, while the R&D rates of Japan, the EU, and the ODC rose slowly by approximate 0.5 percent points from 2000 to 2014. For developing countries, the R&D rate of China rose significantly from 0.89 percent of the GDP in 2000 to 2.04 percent in

Table 4
Calibration outcomes.

	Regression analysis	Z-test	ANOVA
	Correlation coefficient	Z value	F value
GDP	0.9960***	0.4834	0.2337
Current account balance	0.9214***	0.0665	0.3678
Energy use	0.9958***	0.0402	0.0016
Carbon emission	0.9946***	0.0168	0.0003

Note: *** Significant at the 1 percent level.

Table 3
Parameter of the relationship between tech-shock and knowledge stock (1×10^{-5}).

	CHN	USA	JPN	EU	IND	RUS	ODC	HDC	MDC	LDC
$c^\rho_{j,t}$	2.7486	3.1119	−1.8432	2.0534	0.4239	2.4382	−0.4171	−5.5618	−0.5761	−2.3780

2014, while the rate of India rose much more slowly, by only 0.12 percent points from 2000 to 2011. The R&D rate of Russia also ranged between 1.0 and 1.1 percent. Although the R&D data of many other developing countries are missing from the World Bank database [52], the existing data show that the R&D rate of the HDC rose from 0.38 to 0.54 percent, and the rates of the MDC and LDC fluctuated around 0.15 percent. To depict the climate-economy effects of an R&D improvement, the R&D investment rates of countries in the baseline scenario are assumed to be fixed at their initial values (see in Table 1).

An increase in R&D will result in a lower marginal R&D product [53]. While economic output is limited, the R&D expenditure cannot increase at a tremendous rate continuously, as is the case of China over the last 10 years. A periodic slowdown of R&D growth has been long observed, both globally and nationally [54–55]. In fact, global R&D data from the World Bank [52] show periodic ups and downs during last 20 years, with an absolute growth of the R&D investment rate of only 0.12 percent points.

In this study, referencing the rising R&D time-path dynamics of Stadler [56], the historical R&D expenditure data are fitted by the logistic curve estimation method to obtain the estimated curves of the natural R&D investment rate growth of countries in the future. Considering that the world average R&D rate increased by 0.12 percent points during the past 20 years, we set the upper bond in Scenario 1 to 4 percent as the highest R&D rate in 2014 is 3.5 percent of the GDP (Japan). The dynamics of the R&D investment rates of the countries in Scenario 1 are listed in Table 5. It is worth noting that, because of the overall downtrend of R&D rates of Russia, the MDC, and LDC between 2000 and 2014, their R&D rates also decline slightly during the simulation period for Scenario 1.

For achieving their short-term mitigation goals, numerous countries considered the energy R&D for the low-carbon technological progress as a critical approach in their presented INDCs, such is the case of Brazil, Canada, China, New Zealand, Norway, South Africa, and Vietnam. In Scenario 2, on the basis of the natural growth of the overall R&D investment rate from Scenario 1, we consider the growth of energy R&D expenditure independently from overall R&D investment. The R&D budget data of IEA [57] shows that the both energy R&D and its GDP share for the OECD countries during the past 10 years were highly unstable. However, Norway, Finland, and Japan had the highest GDP shares for the public energy R&D budget, which was obviously higher than for other OECD countries. In 2014, Norway was the country with the largest GDP share for the energy R&D budget (0.161 percent) in the OECD countries, while in 2013 the largest GDP share was held by Finland (0.134 percent). Beside, among developing countries, the GDP share of the energy R&D budget of China has increased fast. From 2008 to 2009, it increased from 0.19 to 0.24 percent, even higher than those of developed countries [58]. Therefore, in Scenario 2, for realizing the INDC targets, it is assumed that the energy R&D rates of all the countries reach 0.5 percent of GDP by 2020, and then increase to 1 percent linearly by 2100. This R&D setting is implemented since 2016, and the R&D investment rates between 2007 and 2015 are as same as those in Scenario 1.

In Scenarios 3 and 4, for realizing the 2 and 1.5 °C global warming targets in Paris Agreement, the R&D investment rates of various countries are relatively radical. In Scenario 3, the energy R&D rates increase to 0.8 percent of GDP by 2020 and reach 1.5 percent by 2100, while the overall R&D investment rates increase to approximately 9.5 percent by 2100. In Scenario 4, the energy R&D rates increase to 1.2 percent of GDP by 2020 and reach 2 percent by 2100, while the overall R&D rates reach approximately 22 percent by 2100. The R&D investment rates of countries in Scenarios 2, 3, and 4 in 2025, 2050, 2075, and 2100 are listed in Table 5. These R&D settings are also implemented since 2016.

The other parameter values of these four scenarios are the same as those for the baseline scenario. Due to the uncertainty of simulation outcomes caused by the stochastic mechanism of the technological progress, every scenario in this study has been simulated 100 times, and the analyses of all scenarios are based on the statistics of those simulations.

Fig. 1 shows global warming during the simulation of the baseline and the four R&D scenarios. Table 6 shows the global warming by 2100 for the five scenarios. In the baseline, the global mean surface temperature increases by approximately 3.22 °C in 2100 from the pre-industrial level, exceeding the 2 °C global warming limit in the Copenhagen Consensus and Paris Agreement.

As the R&D investment rates increase, the global warming of 2100 in the four R&D scenarios decreases compared with the baseline. In Scenario 1, the global warming by 2100 decreases to 3.04 °C, and in Scenario 2, the global warming by 2100 decreases further to 2.87 °C. The two radical scenarios show that the global warming targets can theoretically be achieved by rising R&D. While the R&D rates of countries increase to higher than 9 percent of the GDP after 2020, the global warming decreases to 2 °C, achieving the main global warming control target in the Copenhagen Consensus and Paris Agreement. In Scenario 4, global warming reaches its peak around 2066, and the ambitious 1.5 °C target can be achieved in 2100 when the R&D rates of countries rise to higher than 20 percent of the GDP after 2020.

Table 5
Overall R&D investment rates as a percentage of the GDP by country in three scenarios (%).

		CHN	USA	JPN	EU	IND	RUS	ODC	HDC	MDC	LDC
Scenario 1	2025	2.94	2.85	3.73	2.08	0.64	0.98	2.67	0.71	0.12	0.13
	2050	3.78	3.17	3.93	2.61	0.86	0.95	3.57	1.36	0.10	0.10
	2075	3.89	3.40	3.99	3.00	1.12	0.92	3.92	2.12	0.10	0.09
	2100	3.90	3.57	4.00	3.25	1.39	0.89	3.98	2.74	0.10	0.09
Scenario 2	2025	3.45	3.34	4.19	2.58	1.17	1.50	3.18	1.24	0.65	0.66
	2050	4.45	3.82	4.55	3.27	1.55	1.63	4.23	2.04	0.79	0.79
	2075	4.71	4.21	4.76	3.82	1.96	1.75	4.76	2.96	0.94	0.93
	2100	4.88	4.53	4.93	4.22	2.39	1.88	4.98	3.74	1.10	1.09
Scenario 3	2025	8.82	8.81	8.77	8.82	8.84	8.83	8.80	8.84	8.84	8.84
	2050	9.04	9.03	8.99	9.04	9.06	9.05	9.02	9.06	9.06	9.06
	2075	9.26	9.25	9.21	9.26	9.28	9.27	9.24	9.28	9.28	9.28
	2100	9.48	9.46	9.43	9.48	9.50	9.49	9.45	9.50	9.50	9.50
Scenario 4	2025	21.23	21.21	21.18	21.23	21.25	21.24	21.20	21.25	21.25	21.25
	2050	21.48	21.46	21.43	21.48	21.50	21.49	21.45	21.50	21.50	21.50
	2075	21.73	21.71	21.68	21.73	21.75	21.74	21.70	21.75	21.75	21.75
	2100	21.98	21.96	21.93	21.98	22.00	21.99	21.95	22.00	22.00	22.00

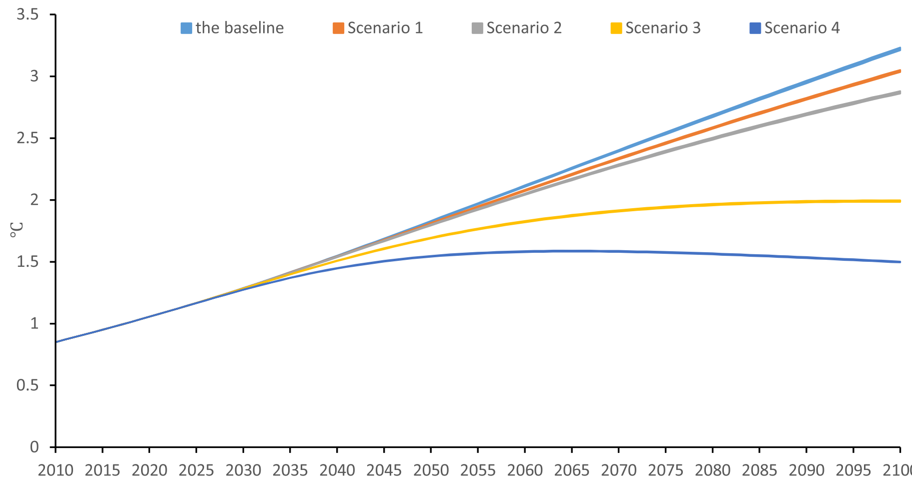

Figure 1. Global warming in the baseline and the four R&D scenarios. The range represents 95% scenario uncertainty.

Table 6
Global warming in 2100 from the pre-industrial level (°C) for the baseline and the four R&D scenarios, and confidence intervals of uncertainty.

	Mean	50% confidence interval	95% confidence interval
The baseline	3.2197	3.2167–3.2225	3.2105–3.2329
Scenario 1	3.0428	3.0404–3.0457	3.0332–3.0511
Scenario 2	2.8712	2.8685–2.8743	2.8608–2.8802
Scenario 3	1.9900	1.9882–1.9919	1.9843–1.9961
Scenario 4	1.4977	1.4966–1.4985	1.4939–1.5020

3.1. Carbon emissions in INDC years

On the basis of the submitted mitigation objectives and targets of the INDCs, this section compares the emissions of countries by their target years with their main post-2020 mitigation targets in their INDCs. Except the USA for which the INDC year is 2025, 2030 is set as the target year for the other countries and groups. The mitigation actions of the INDCs are all measured in the terms of GHGs, but CIECIA only includes carbon emissions. According to the country GHG and CO2 emissions from the CAIT climate data of the World Resources Institute, the emissions of GHG and CO2 have a relationship of synchronization. The proportion of CO2 to total GHG is stable at approximately 70 percent. Therefore, in this study, all the mitigation targets are converts to be measured by carbon emissions.

Table 7 depicts the reductions of carbon emissions by country in the four R&D scenarios from 1990, 2005, and the INDC target years in the baseline, as well as the reductions of carbon intensity. In Scenario 1, the carbon emissions per unit of GDP of China by 2030 is lowered by 67 percent from its 2005 level, achieving its INDC mitigation target of lowering carbon intensity by 60–65 percent in 2030. The mitigation target for India is a 33 to 35 percent emissions intensity reduction by 2030 from its 2005 level, and India also achieves its target in Scenario 1 by reducing its carbon intensity by 41 percent. Japan also realizes its INDC target of reducing carbon emissions by 25.4 percent from its 2005 level in Scenario 1 in which its carbon emissions are reduced by approximately 35 percent.

Compared to Scenario 1, the carbon emissions in Scenario 2 change slightly. The developing countries improve their carbon emission reductions in 2030 by more than 1 percent, but are still far from their INDC targets. In Scenario 3, the carbon emissions of the USA in 2025 decrease by 25.78 percent from its 2005 level, approaching its INDC target of reducing carbon emissions by at least 26 percent. Russia also achieves its INDC target of carbon reduction in 2030 by 25 percent from its 1990 level in Scenario 3, by lowering its emissions by approximately 35 percent. The carbon emissions of the EU in 2030 in Scenario 3 are 24 percent below the 1990 level, still far from its 40 percent reduction target. The EU cannot achieve its INDC target until its R&D investment rate increases to the level for Scenario 4, in which the EU reduces its emissions by 50.67 percent below the 1990 level.

Table 7
Mean values of reductions of carbon emissions and intensities by country from their base years to INDC years (%).

	Base year	CHN	USA	JPN	EU	IND	RUS	ODC	HDC	MDC	LDC
Scenario 1	1990 emission	−539.96	5.41	22.80	14.66	−540.36	9.42	−38.85	−109.44	−284.97	−204.09
	2005 emission	−155.07	20.53	34.88	15.33	−213.63	−37.06	16.63	−70.38	−129.54	−135.45
	baseline emission	6.66	0.68	1.21	0.62	0.18	−0.09	1.66	−0.11	0.21	0.22
	2005 intensity	67.33	47.26	44.39	38.88	40.53	61.56	50.68	39.85	57.55	31.87
Scenario 2	1990 emission	−525.44	5.78	23.55	15.55	−524.40	11.78	−37.19	−105.69	−277.79	−198.55
	2005 emission	−149.29	20.84	35.52	16.21	−205.82	−33.49	17.62	−67.32	−125.27	−131.16
	baseline emission	8.77	1.08	2.17	1.66	2.67	2.52	2.83	1.69	2.07	2.04
	2005 intensity	67.98	47.35	44.66	39.24	41.84	62.45	51.06	40.69	58.20	32.89
Scenario 3	1990 emission	−395.67	11.66	30.88	24.47	−358.15	35.13	−24.47	−68.50	−211.25	−149.67
	2005 emission	−97.56	25.78	41.70	25.06	−124.39	1.85	25.26	−37.07	−85.59	−93.31
	baseline emission	27.70	7.25	11.55	12.04	28.58	28.33	11.84	19.46	19.32	18.08
	2005 intensity	74.74	50.39	48.28	44.61	58.93	73.22	54.46	52.53	67.84	47.38
Scenario 4	1990 emission	−188.60	29.25	57.77	50.67	−145.82	65.30	13.39	2.47	−89.63	−54.77
	2005 emission	−15.03	40.56	64.38	51.06	−20.39	47.49	47.99	20.66	−13.07	−19.84
	baseline emission	57.91	25.72	45.96	42.56	61.68	61.66	38.66	53.38	50.84	49.22
	2005 intensity	84.46	57.26	60.09	56.65	76.42	84.77	62.98	68.93	78.71	64.44

There are many different forms of carbon reduction targets, e.g., intensity reduction, emission reduction, on the basis of the different base years. In addition, several countries still have not submitted their INDC actions, and some submitted INDCs lack the necessary details of mitigation actions [59]. Therefore, it is difficult to summarize the reduction targets of the ODC, HDC, MDC and LDC. However, it is feasible to judge whether those country groups achieve their targets by comparing the carbon reductions in scenarios with the abatement targets of their main member states. In Scenario 3, the carbon emissions of the ODC in 2030 are 25.26 percent below the 2005 level and the carbon intensity is 54.46 percent below the 2005 level, approaching the gross reduction targets of its main member states, e.g., Canada of which the INDC target is for reducing emissions in 2030 by 30 percent below the 2005 level; Australia (28 percent below the 2005 level); Israel (26 percent below the 2005 level); and New Zealand (30 percent below the 2005 level).

Among the main carbon emission members of the HDC, MDC, and LDC, Ukraine promised to not exceed 60 percent of its 1990 level, equaling to 1.4 times higher than its 2005 level. Brazil intended to reduce its emissions by 43 percent below 2005 levels in 2030. South Africa intended to reduce its emissions to a range between 398 and 614 MtCO2e, equaling to 35 percent growth from its 2005 level at least; Mexico intended to unconditionally reduce 22 percent of its emissions below the baseline for the year 2030. Turkey intended to reduce up to 21 percent from the baseline level by 2030. Thailand intended to reduce its emissions by 20 percent from the baseline level by 2030. Indonesia intended to reduce unconditionally 29 percent of emissions against the baseline in 2030. Vietnam intended to reduce emissions by 8 percent by 2030 compared with the baseline. Malaysia intended to reduce its carbon intensity in 2030 by 35 percent from its 2005 level. The INDC targets of Angola, Venezuela, Colombia, Nigeria, Morocco, Algeria, Iran and Niger are 35, 20, 20, 20, 13, 7, 4 and 3.5 percent reductions by 2030 below their baseline levels. The targets of Cameroon and Iraq are 32 and 13 percent reductions by 2035 below their baseline levels. The gross carbon emissions of those above countries account for approximately 70 percent of the total carbon emissions of the HDC, MDC and LDC.

In Scenario 3, the carbon reductions of the HDC, MDC and LDC are approximately 20 percent below their baseline levels, and in Scenario 4, their carbon reductions are approximately 50 percent below their baseline levels. If those specific INDC targets are applied to the 2014 national carbon emissions (from EIA [44]), the reduction targets of the HDC, MDC and LDC will be approximately 14, 24 and 17 percent from their baseline levels in 2014 respectively. Considering the INDCs without specific targets, the gross carbon reduction targets will not exceed 24 percent below their baseline levels. Therefore, the HDC, MDC, and LDC approach their INDC targets in Scenario 3, while in Scenario 4, their INDC targets can all be achieved definitely.

3.2. Carbon emissions and economies by 2100

Fig. 2 shows the cumulative additional R&D expenditures by country of the four R&D scenarios compared to those in the baseline. Because of the radical R&D rates, the additional R&D expenditures are enormous in Scenarios 3 and 4. The additional overall R&D expenditure of China in Scenario 4 is much larger than those of the other countries, reaching 590 trillion USD (in 2005's constant price), followed by the HDC and MDC. The additional R&D expenditures of the USA and EU are also larger than 300 trillion USD in Scenario 4, whereas those of Japan and Russia are relatively lower because of their limited economic scales in the future.

Figs. 3 and 4 show the cumulative carbon emissions by country of the four scenarios between 2007 and 2100, and the reduction rates compared to the baseline. The developing countries reduce much more carbon emissions than developed countries, even when the developed countries have also improved their R&D input in Scenarios 2, 3, and 4. The LDC achieves the highest reduction rates among the countries. In Scenario 4, the reduction rate of the LDC reaches 91.96 percent, followed by India, the MDC and HDC of which the reduction rates are all higher than 80 percent. In Scenario 4, the absolute cumulative Chinese carbon reduction from the baseline is 236.88GtC, more than any other country. However, China is still the biggest carbon consumer in the world, followed by the USA, EU, and HDC whose emissions are all more than 30GtC. The reductions of developed countries are much fewer than

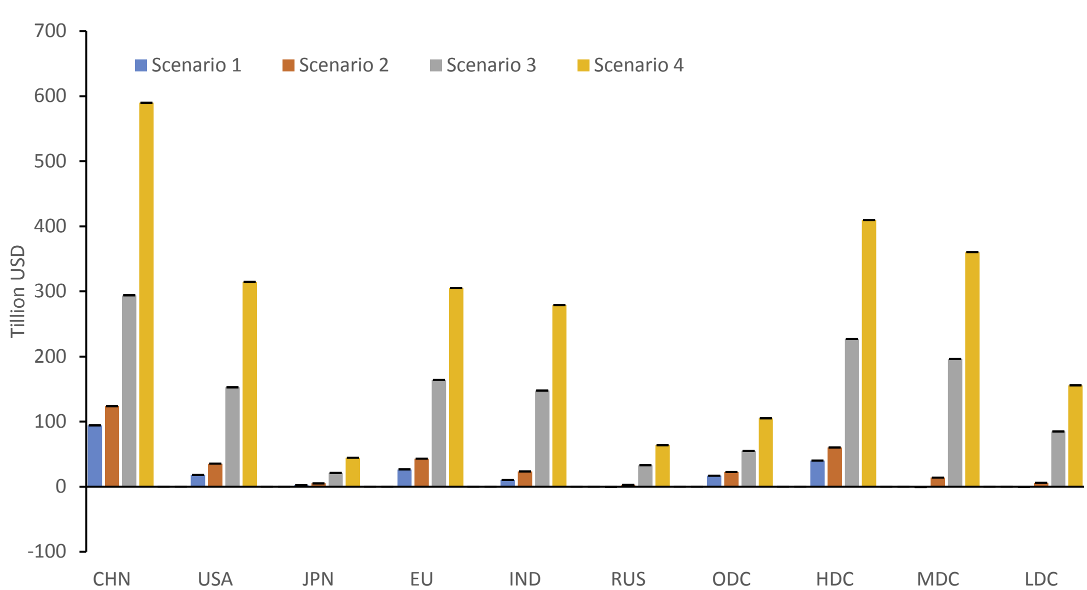

Figure 2. Cumulative additional R&D expenditures in the four R&D scenarios. The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

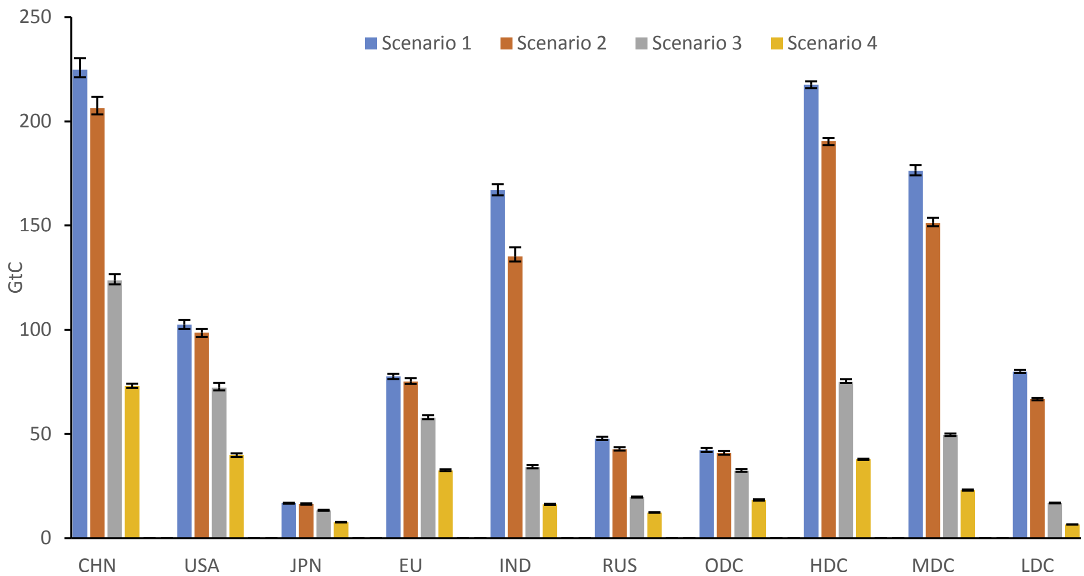

Figure 3. Cumulative carbon emissions by country for the four scenarios (GtC). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

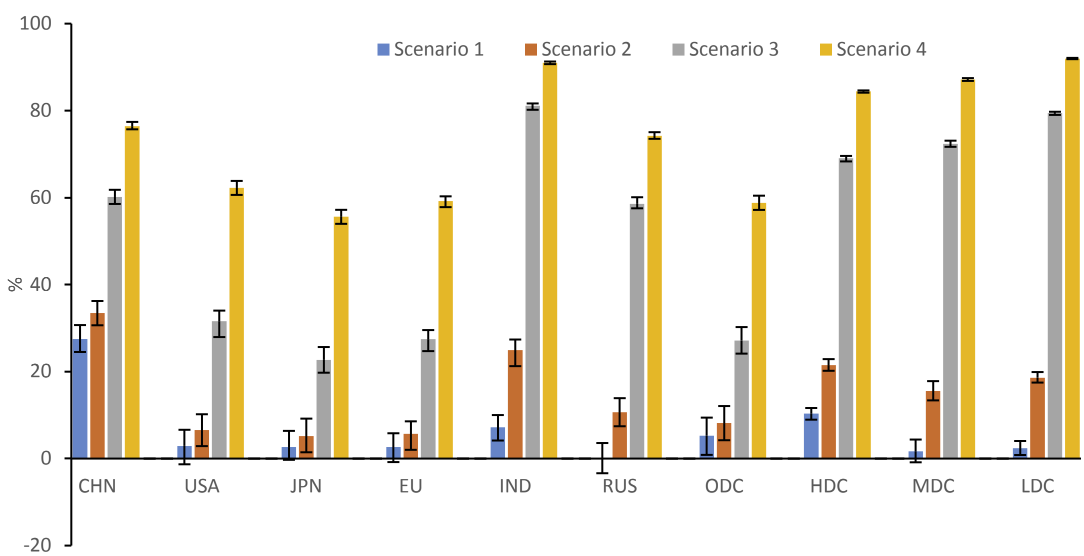

Figure 4. Reductions of the cumulative carbon emissions by country compared to the baseline for the four scenarios (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

developing ones. The reduction rates of the USA, EU, and ODC in Scenario 2 are all less than 10 percent, and that of Japan is even less than 6 percent. In Scenario 4, under such radical R&D rates, the reductions of Japan and the ODC are still less than 55 percent, less than the reduction rates of developing countries in Scenario 3. In Scenario 4, the global proportion of carbon consumptions for developed countries increases to more than 36 percent, while in the baseline, this proportion is less than 20 percent.

The main reason for this phenomenon is that developed countries always have higher initial knowledge stocks, process technological levels and R&D investments in the baseline, and thus the improved R&D inputs cannot affect their knowledge stocks as much as they do in developing countries in those four scenarios. Another reason is that, different from the developing countries that still have strong demands on carbon consumption for the process of industrialization, the carbon emission curves of developed countries have been on the decline and will remain steady or keep downward in the baseline. That means their reduction potential for carbon consumption is limited.

Fig. 5 shows the changes of cumulative utilities by country compared to the baseline for the four R&D scenarios. In Scenario 1, the countries improving their R&D inputs obtain more utilities. In Scenario 2, the utilities of developed countries decline to less than their baseline levels because of the additional energy R&D inputs, whereas those of Russia, the MDC and LDC are still less than their baseline levels because of insufficient R&D inputs. In Scenario 3, the cumulative utility of the LDC increases by approximately 11.92 percent, followed by the MDC and India whose utilities increases by more than 6 percent. However, the utilities of developed countries and China decrease further because of the excessive R&D inputs and the increasing economic competition from developing countries. In the cases of China, Japan, and the USA, it indicates that

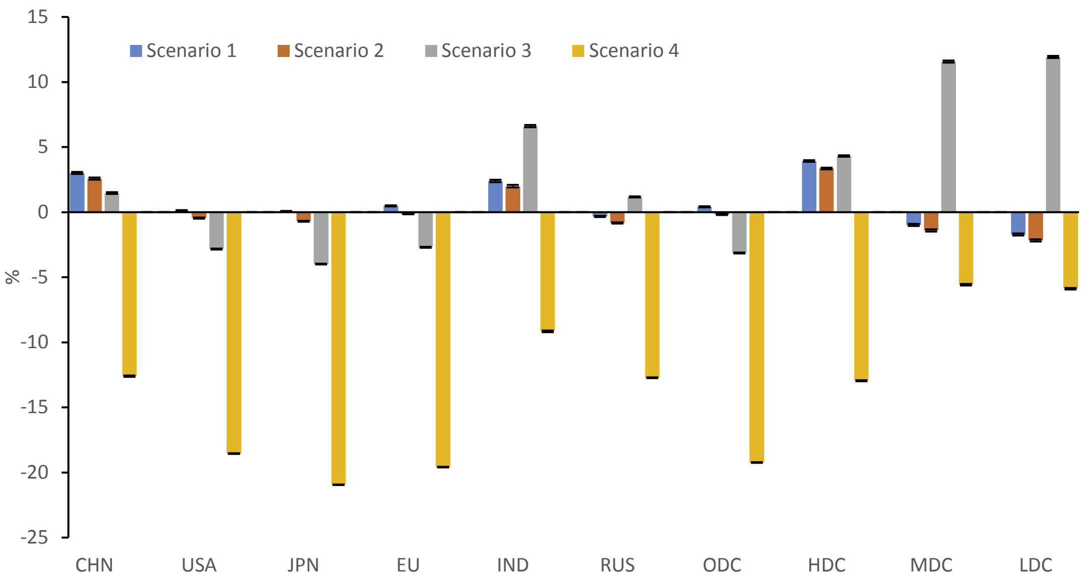

Figure 5. Changes in cumulative utilities for the countries compared to the baseline for the four scenarios (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

raising the average overall R&D rate to approximately 4 or 5 percent of GDP is the limit to obtain highest utility improvements. From Scenarios 3 to 4, the utilities decline significantly. The cumulative utilities of all countries are less than their baseline levels in Scenario 4. Among them, the utilities of the MDC and LDC decrease by approximately 6 percent compared to the baseline level, and those of China, India, Russia the HDC decrease by more than 10 percent. The utilities of developed countries decrease by more than 15 percent.

This result shows that R&D cannot completely replace the demand for fixed capital in the production process. R&D input comes at the cost of fixed capital investment. Excessive R&D inputs will damage economic development by decreasing the investment in sectoral production and decreasing the fixed capital stock in turn. Therefore, the improvement in the economy due to R&D investment is limited, as capital investment in the sectors is still the foundation of economic development.

Among the countries, the utility improvements in developed countries are lower in Scenario 1, even under similar increasing ranges for R&D input as the developing countries such as China, India, and the HDC. The utility of Japan and the USA in Scenario 1 only increase by 0.11 and 0.06 percent, respectively. In Scenario 4, their utility losses are much higher than the developing countries. The main reasons are similar to those of emission reduction. On one hand, developed countries have both higher initial knowledge stocks and R&D input, thus the increased R&D input cannot improve the cumulated utilities as much as those of developing countries. On the other hand, the developed countries have to face more intense economic competition from the increase of the developing countries' R&D input. That also leads to lower increases of utility in the developed countries. This result indicates that improving R&D input to promote technological progress is an effective approach for developing countries to narrow the economic gaps between them and developed countries.

In the *U.S.-China Joint Announcement on Climate Change* released on November 12, 2014, China promised to achieve a CO_2 emission peak before 2030. This is the first time that China and the United States have had an agreement on their post-2020 emission abatement targets and actions. In its INDC, China emphasized again the intention of achieving the peak of carbon dioxide emissions around 2030 and making the best efforts to peak early. As Fig. 6 shows, the carbon emission peak for China is earlier and its peak emissions decline when the R&D input is improved. In Scenario 1, the carbon peak for China appears in 2030 and the mean peak emissions decrease by approximately 8 percent to 3.82GtC, achieving the target in both *U.S.-China Joint Announcement on Climate Change* and the INDC. In Scenario 2, the carbon peak for China appears in 2029 with 3.73GtC peak emissions. In Scenario 4, China achieves its carbon peak in 2020, and the peak emissions decline to approximately 3.10GtC.

The improvement of R&D input obviously promotes the reduction of carbon emissions for countries and mitigates global warming. However, as the main carbon emitters, e.g., China, the USA, India, Russia, and the other developing countries have approached or overachieved their INDC targets, global warming by 2100 still reaches 2 °C. That means if there are not further intensified emission reductions, the mitigation targets of 2 or 1.5 °C will be very difficult to achieve.

3.3. Technology transfer and diffusion

In this section, we design a technology transfer and diffusion module on the basis of the agent-based model of Wang et al. [60] to reflect the technology transfer from countries or regions with advanced low-carbon technologies, such as Japan and the EU, to developing countries such as China and India. In the model of Wang et al. [60], the technology diffusion is realized on the basis of individual imitation. When the technology imitator has decided on its target, it would obtain an accelerated R&D speed or imitating speed, and the gap between the mock technology and its own will be decomposed into an accelerated and an independent R&D part. The accelerated part can be achieved through the accelerated speed, whereas the independent part needs to be researched and developed by the imitator for patent protection.

Here, this mode was adopted and modified. The developing countries accomplish technology-pursuit by improving their paces of the technological progress, while the technology gap of the low-carbon technology level between them and the developed countries is larger than the imitating threshold. In the other words, a sector in the developing countries will have a higher variance of

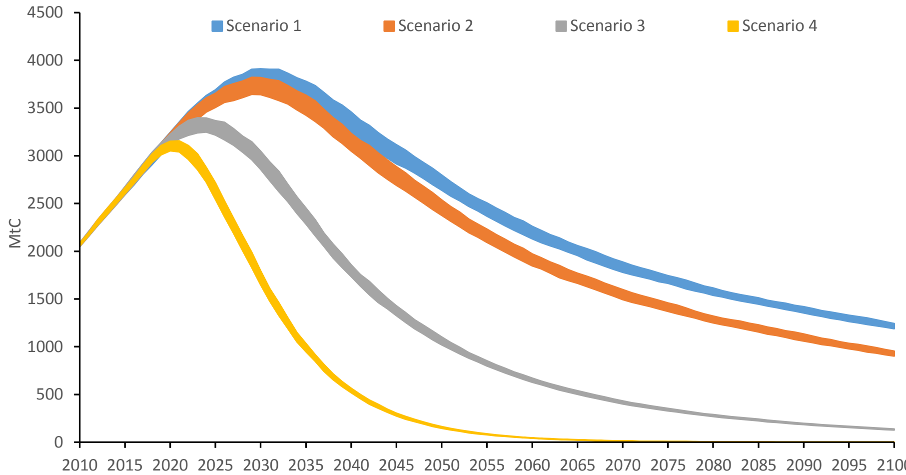

Figure 6. Carbon emission trends of China for the four scenarios (MtC). The range represents 95% scenario uncertainty.

stochastic technology shock on its intermediate energy input coefficient if it is higher than the imitation range of the average level in the developed countries. To reflect this technology transfer and diffusion mechanism, Equation (12) for developing countries can be written as

$$\ln\left(a'_{k,j,i,t}\right) = \ln\left(a^{*}_{k,j,i,t,n}\right) + \varepsilon_{j,k,i,t,n}$$
$$\varepsilon_{j,k,i,t,n} \sim \begin{cases} N\left(0; s\rho^{j}_{k,t}\right) & \text{if } k = Enrg \text{ and } a_{j,k,i,t,n} > (1+W)\overline{a}_{d,k,i,t} \\ N\left(0; \rho^{j}_{k,t}\right) & \text{otherwise} \end{cases} \tag{21}$$

where s is the accelerated R&D speed (imitating speed), W is the imitating threshold for the developing countries to imitate the more advanced low-carbon technologies of the developed countries, and $\overline{a}_{d,k,i,t}$ is the average level of the intermediate energy product input that sector i of the developed country actually uses per unit of output in the production process. Therefore, $(1+W)\overline{a}_{d,k,i,t}$ indicates the lower bond of the imitation range for sector i of developing country j. According to Equation (16), only the intermediate energy input coefficients in the developing countries have an accelerated R&D speed, the others still following the former process technological progress mode.

To research the carbon mitigation effect of the technology transfer and diffusion, four scenarios are designed to change the accelerated R&D speed and the imitating threshold towards accelerating the decline of the intermediate energy input coefficients for developing countries. The other parameter values of these four scenarios are the same as those in Scenario 2. The values of the accelerated R&D speed and imitating threshold are listed in Table 8.

Table 9 shows the global warming in 2100 (°C) from the pre-industrial level in the four technology transfer scenarios. The energy-saving technology transfer from developed to developing countries is quite effective in declining global warming. When the imitating threshold is 40 percent, a four times faster R&D speed decreases the global temperature rise to 2.59 °C, while an imitating threshold of 20 percent, decreases the global temperature increase to 2.50 °C by 2100 under the four times faster R&D speed of the developing countries. Compared with Scenario 2, the global warming in Scenario 8 decreases by approximately 0.4 °C, without any supplemental R&D expenditure. Therefore, despite that the 2 °C target cannot be achieved, the technology transfer and diffusion have a significant potential on carbon abatement that should be of concern to climate policy makers.

Table 8
Accelerated R&D speeds and imitating thresholds in the four scenarios.

	Imitating threshold (%)	Accelerated R&D speed
Scenario 5	40	2
Scenario 6	40	4
Scenario 7	20	2
Scenario 8	20	4

Table 9
Global warming in 2100 from the pre-industrial level (°C) for the four scenarios and confidence intervals of uncertainty.

	Mean	50% confidence interval	95% confidence interval
Scenario 5	2.6382	2.6349–2.6416	2.6290–2.6457
Scenario 6	2.5958	2.5926–2.5998	2.5791–2.6066
Scenario 7	2.5630	2.5596–2.5660	2.5569–2.5694
Scenario 8	2.5039	2.4999–2.5078	2.4911–2.5177

Fig. 7 shows the changes of the cumulative utilities by country for the simulations of the four scenarios, compared to Scenario 2. All the cumulative utilities of all countries in these four scenarios are higher than those of Scenario 2, mainly because of the climate welfare brought by curding the global temperature rise. As global warming decreases from Scenario 5 to 8, the utilities of countries increase. In Scenario 8, the cumulative utility of India increases by 1.45 percent compared with Scenario 2, followed by China, the MDC, and LDC; the utilities of the developed countries also rise by approximately 1.2 percent.

Fig. 8 shows the reductions of the carbon emission intensities by country in 2100 for the four scenarios compared to Scenario 2. Along with the increase of the imitating speed and decrease of the imitating threshold, the carbon intensities of the developing countries obviously decrease by 2100. In Scenario 8, as the accelerating R&D speed increases to 4, the carbon intensity of India by 2100 decreases by approximately 50 percent compared with that of Scenario 2. The reductions for the LDC, China, and Russia are also above 35 percent. Generally, the carbon intensities of the developed countries also decrease slightly, because the climate welfare brought by curbing global warming promotes the economic growth of developed countries, which in turn leads to more R&D

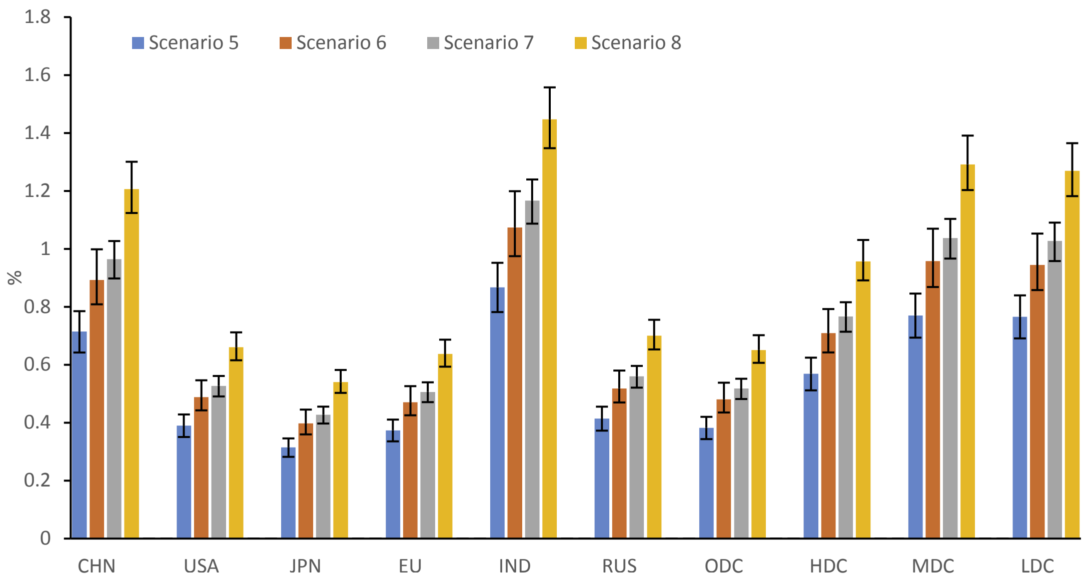

Figure 7. Changes in cumulative utilities for the countries compared to Scenario 2 for the four scenarios (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

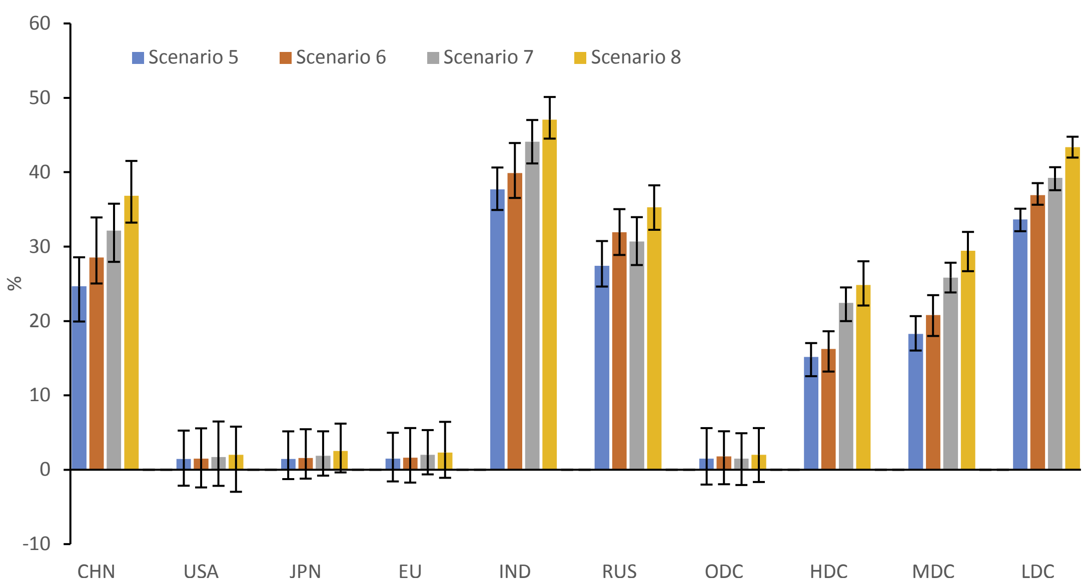

Figure 8. Reductions of the carbon emission intensities by country in 2100 compared to Scenario 2 for the four scenarios (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

investments under the same R&D rates.

Fig. 9 shows the cumulative carbon reductions by country for the four scenarios compared to Scenario 2. In Scenario 8, the cumulative carbon emission reduction of India reaches approximately 50 percent compared to Scenario 2, followed by the LDC, China, and Russia whose reductions are 37.79, 29.24, and 26.27 percent, respectively. Different from developing countries, the carbon emissions of the technology sources (i.e. the developed countries) in these four scenarios increase slightly. This is also mainly because of the increased climate welfare that promotes economic growth and leads to more carbon emissions, which cannot be offset by the decreased carbon intensities of the developed countries as these R&D investment rates maintain the levels in Scenario 2 for these four scenarios.

4. Conclusions and discussion

In this study, we used a climate-economy IAM CIECIA to study the reduction effect of R&D policy and its economic impact under the background of INDCs. This IAM employed a multi-country-sector general equilibrium model developed from Jin [33] as its economic core. A process technological progress mechanism driven by R&D input and knowledge stock accumulation was adopted to depict the emerging and self-selection of the process technologies, including the energy-saving ones. Besides, a technology diffusion mode based on individual imitation was adopted in this IAM. On

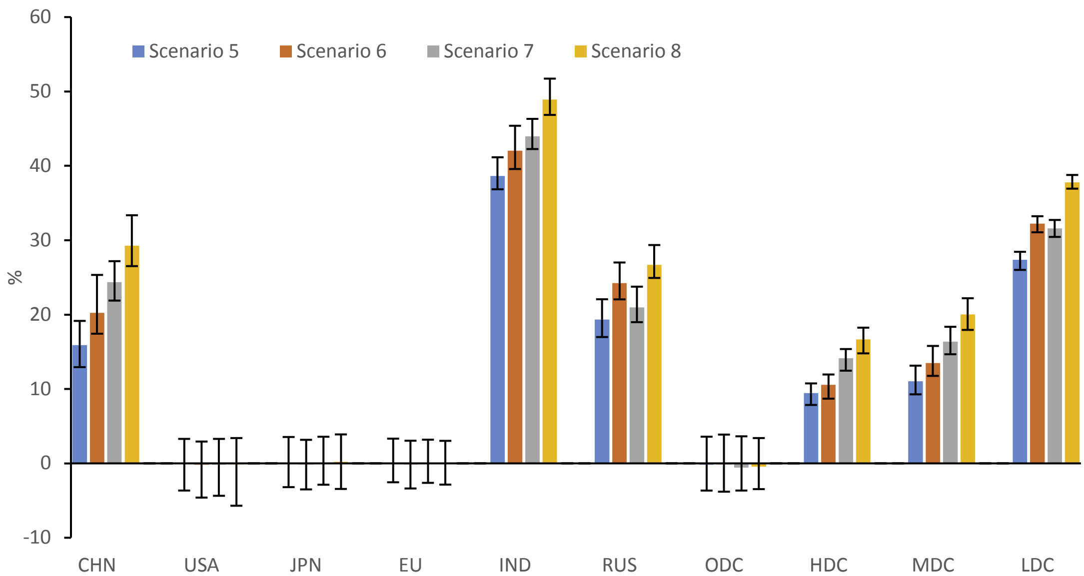

Figure 9. Reductions of the cumulative carbon emissions by country compared to Scenario 2 for the four scenarios (%). The bars indicate means across the simulations. The error bars represent the 95% confidence interval of the scenario.

the basis of CIECIA and its baseline scenario, eight R&D scenarios were designed to study global climate mitigation, carbon reduction effects, and the economic impacts of R&D policies, as well as the reduction effects of technology transfer and diffusion for INDCs. The conclusions derived from the scenario simulations are listed as follows.

The improvement of R&D input promotes carbon reductions for countries and mitigates global climate change. The economies of countries are also improved when the R&D rate increases moderately, avoiding reduction cost, which is always a serious problem in global carbon mitigation. China will also achieve its mitigation target in the *U.S.-China Joint Announcement on Climate Change* in Scenario 1 by achieving its carbon emissions peak in 2030. However, most of the major emitters will not achieve their INDC targets while raising their R&D investment rates up to this level. In Scenarios 3 and 4, as all the countries increase their R&D investment rates to 9.5 and 22 percent of the GDP by 2100, the global warming by 2100 is controlled to below 2 and 1.5 °C above pre-industrial levels, respectively. However, the countries suffer heavy economic losses in Scenario 4 because of excessive R&D expenditure, especially those developed ones.

The developing countries relatively achieve both more carbon reduction and utility improvement compared to developed countries even under a similarly rising range of R&D investment rates. This result is mainly because developed countries have relatively higher initial knowledge stocks and process technological levels, as well as higher R&D investment rates under the baseline. Those lead to less of the promoting effect from R&D policy on both the economy and emission reduction for the developed countries. In addition, the strong demands for carbon consumption in the developing countries also brings higher reduction potentials to their process of industrialization, compared to those of the developed countries that have been industrialized.

It is worth noting that although most of the countries including China, India, and other developing countries that account for the major proportion of carbon consumption will have approached or overachieved their INDC targets by approximately 2030 in Scenario 3, the global warming by 2100 will still be close to 2 °C. That indicates that if the global mitigation participants do not intensify their carbon reduction efforts in the post-INDC period, not only will the 1.5 °C climate mitigation target not be reached but also the 2 °C targets will be difficult to achieve.

Although R&D policy significantly effects global carbon abatement, it is worth noting that when limited by the actual R&D ability, it will be difficult to increase the R&D investment rate to such a high level as in Scenarios 3 and 4. This limitation is also indicated in the historical trends of the research and development expenditures by country from World Bank Open Data [52]. Therefore, the radical R&D rates in Scenarios 3 and 4 would be very difficult to realize. In addition, the economic loss under such radical R&D rates will also impede their implementation. Considering the actual R&D abilities and the economic impact of R&D improvement, raising the R&D rate to approximately 4 or 5 percent of the GDP might be the limit of R&D improvement climate mitigation.

On the basis of R&D improvements, technology transfer and diffusion from countries with advanced low-carbon technologies to developing ones is also an effective and important approach to improving energy efficient and reducing carbon emissions for the latter. While the imitating threshold is 20 percent and the imitating speeds of the developing countries can be four times higher than their independent R&D speeds, global warming can decrease by approximately 0.4 °C in 2100 without any supplemental R&D expenditure. However, the 2 °C target cannot be achieved in those four scenarios.

From the perspective of policy design, the R&D policy fits when combined with other emission reduction measures to comprise a policy portfolio on the basis of an integrated abatement approach. That can give full play to the advantages of R&D policy for economic promotion to ease economic losses caused by other emission reduction measures, especially in the developing countries, to reduce the reduction costs and improve the feasibility of the policy portfolio. In fact, we have had several studies on the policy portfolio of R&D improvement and other climate mitigation measures such as carbon tax, investment limit on energy-intensity sectors, and carbon cap. One of those results showed that using carbon tax revenue to improve R&D input would both realize the Pareto improvement in economies and achieve the 2 °C global warming target [61].

CIECIA focuses on the macroeconomic processes and interactions between countries and sectors under global climate change. Therefore, the energy system of this model is relatively rough. In addition, the process technological progress only refers to the decline of the entire unitary cost of sectors on a macro level, reflecting the overall improvement of production progress in general. The specialized investment, development and transfer of individual CO2 reduction or removal technologies such as carbon capture, utilization and storage are excluded. We leave those for further study.

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