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RESEARCH ARTICLE

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Effects of the US withdrawal from Paris Agreement on the carbon emission space and cost of China and India

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Abstract Climate mitigation has become a global issue and most countries have promised their greenhouse gas reduction target. However, after Trump took office as president of the United States (US), the US withdrew from the Paris Agreement. As the biggest economy, this would have impacts on the emission space of other countries. This paper, by using the integrated model of energy, environment and economy/computable general equilibrium (IMED/CGE) model, assesses the impacts of the US withdrawal from Paris Agreement on China, India in terms of carbon emission space and mitigation cost under Nationally Determined Contributions (NDCs) and 2°C scenarios due to changed emission pathway of the US. The results show that, under the condition of constant global cumulative carbon emissions and fixed burden sharing scheme among the countries, the failure of the US to honor its NDC commitment will increase its carbon emission space and decrease its mitigation cost. However, the carbon emission space of other regions, including China and India, will be reduced and their mitigation costs will be raised. In 2030, under the 2°C target, the carbon price will increase by US$14.3 to US$45.3/t in China and by US $10.7 to US$33.9/t in India. In addition, China and India will incur additional GDP loss. Under the 2°C target, the GDP loss of China would increase by US$23.3 to US$72.6 billion (equivalent to US$17.4 to US$54.2/capita), and that of India would rise by US$14.2 to US$43.1 billion (equivalent to US$9.3 to US$28.2/capita).

Keywords Paris Agreement, China and India, the US withdrawal, carbon emission space, mitigation cost

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1 Introduction

The Paris Agreement was signed by 195 parties to the United Nations Framework Convention on Climate Change (UNFCCC), the purpose of which is to tackle climate change to avoid the global temperature in this century from rising by 2°C above the pre-industrial levels, and try to control the rise within 1.5°C. Previous studies have showed that compared with the current policy scenario, the implementation of Paris Agreement is helpful to reduce the global greenhouse gases (GHGs) to a certain extent, but not sufficient enough to achieve the 2°C target [1]. Researchers have proposed a "carbon law" to achieve the 2°C target by halving gross anthropogenic carbon-dioxide (CO_2) emissions every decade and reducing to zero emissions by the middle of this century [2], which raises a more stringent requirement for carbon reduction in each country.

Most countries have already submitted their National Determined Contributions (NDCs). Reference [3] has proposed that the 2°C target could be achieved if most countries adopt ambitious targets. This has been supported by Ref. [4], which has revealed that the global GHGs emission level should be kept below 38 gigatonne CO_2 equivalent ($GtCO_2eq$) by 2030 to achieve a chance of about two-thirds of staying below 2°C in 2100. However, in the same study, the current NDCs are projected to lead to a 50 $GtCO_2eq$ emission level by 2030, indicating that current NDCs efforts are not sufficient to achieve the 2°C target. Therefore, additional reduction efforts are needed by all countries, especially by those countries that rank as the top emitters at present or in the coming decades such as China and India. Although it has been estimated that current domestic climate policies of India and China could lead to lower emission levels than their pledged levels [5], massive pressure and responsibility of reducing CO_2 emission would fall on these two countries due to their increasing share of the world's GHG emission from their rapid economic growth [6].

The fairness of emission allowances for China and India, as well as the possible impact of their NDCs, has been evaluated from multiple perspectives. Reference [3] has evaluated whether NDCs of countries have met the six equity principles of effort-sharing which had been introduced in the IPCC AR5. The results indicates that China's NDC fails to meet any of the six principles under the 2°C target, while India's NDC could conform to most equity principles even under the 1.5°C target. Reference [7] has found a bi-directional causality between CO_2 emissions and coal consumption in both short and long-term in the case of China, but only a short-term causality has been detected in the case of India. Reference [8] has argued that in the case of China, CO_2 emission would decrease when income increases, while for India, a positive relationship could be observed between CO_2 emission and income. Reference [9] has revealed that the mitigation cost of China and India is relatively lower than other major emitters such as the US or Canada under both NDC target and the 2°C target, and could be substantially decreased by establishing the emission trading scheme. To focus on China, Ref. [10] has projected that China would peak its CO_2 emission level by 2026, at 11.20 Gt, which would be achieved by a less than 4.5% annual GDP growth rate by 2030, and a 43% and 45% decrease of energy and carbon intensity, respectively, from 2015 to 2030. However, macroeconomic loss in GDP growth rate is found feasible to be alleviated by emission trading scheme [11–13].

Additionally, Ref. [14] has reviewed the potential of renewable energy in China and discussed whether it could meet the NDC target. The results indicate that the non-fossil energy share could achieve a 20% in primary energy and a 40%–50% in electricity power by 2030. Reference [15] has projected that fossil energy with carbon capture and storage technologies and non-fossil energy would play a major role in the transformation of China's energy system with the application of the 2°C target. Furthermore, co-effects of pursuing NDC has also been discovered such as the expansion of renewable technologies [16], the increase of water consumption of the power sector [17], and the improvement of air quality [18]. In terms of India, Ref. [19] has indicated that the NDC of India could lead to improvements including reductions in air pollution, savings in water and land use, and savings in materials and resource requirements, along with a 30% reduction of GHG and a 25% reduction in primary energy compared to the business as usual (BaU) scenario. Reference [20] has assessed the sectoral feasibility of reducing GHG and achieving the NDC target in India with two proposed factors, namely political/organizational feasibility and techno-economic feasibility. The results show that the most favorable sectors are the road transport sector and the petrochemicals sector, while the electricity, agriculture, and steel sector represent hard cases on feasibility. Reference [21] has proposed other key social challenges India would face along with the NDC target which would be poverty, food security, education, gender equality, water sanitation, and employment.

However, on 1st June 2017, President Trump of the US declared to withdraw from the Paris Agreement. The international society was shocked by this announcement due to the important role that the US played in the international climate negotiation and governance. The impact of the US withdrawal remains uncertain at present. Hopefully, the US withdrawal from the Paris Agreement would not change the development of low-carbon technologies and the transformation of the global climate governance regime, but long-term goals and international cooperation on climate change would be affected [22]. It would cost the world valuable time dealing with climate change, and have negative impacts on diplomatic standing and rising renewable energy market in the US [23]. However, it was also projected that an approximately 26% CO_2 emission reduction could be achieved by 2030 without the defunded Clean Power Plan (CPP) due to the new normal in natural gas prices [24]. In other words, the negative impact on the US CO_2 emission from its withdrawal is possibly limited. From another perspective, the positive effect of the US withdrawal was predicted and proposed taken into consideration that continued US membership in the Paris Agreement would on the contrary damage the administration of the agreement and prevent new opportunities from emerging [25]. Therefore, it is quite urgent to address the important questions such as: How will US withdrawal affect the implementation of Paris Agreement, global climate governance and China's climate policy? How should China react to the new situation? It is necessary to evaluate how will the carbon emission space, carbon price, and macroeconomic costs of other parties be affected by the US withdrawal.

The future GHG emissions in the coming decades are closely related to socioeconomic development and energy consumption, which are subject to high uncertainty. Since the Special Report Emission Scenario (SRES) was released by the Intergovernmental Panel on Climate Change (IPCC) [26], the Representative Concentration Pathways (RCPs) [27–30] and Shared Socioeconomic Pathways (SSPs) [31–34] were also published, in which the global and regional future energy consumption, GHG emissions, air pollutant emissions and land use change were quantified. These long-term scenarios provide a solid foundation for this study. Based on the above SSPs and RCPs, this paper attempts to address the above research questions by combining qualitative and quantitative analysis. Nine scenarios are designed, including a BaU scenario without carbon emissions constraints, and eight counterfactual scenarios in which the US withdrawal from the Paris Agreement to different extents. The key objective is to quantify how the change of emissions pathways of the US after its withdrawal from the Paris Agreement will affect the carbon emission space, carbon price and macroeconomic costs of four key players of global climate regime, namely, China, the US, the European Union (India), to achieve both the Nationally Determined Contributions (NDCs) and 2-degree (2°C) targets.

2 The IMED/CGE model

This paper uses the integrated model of energy, environment and economy/computable general equilibrium (IMED/CGE), which is a global dynamic multi-region, multi-sector computable general equilibrium (CGE) model of China's provincial and the global economy developed at Peking University [35–37]. This model and its variant versions have been used to analyze the energy and climate mitigation policies, economy, air pollution reduction, human health at the national [38–40] and provincial levels [35,37,41–47] of China. A CGE model is usually used to evaluate the impacts of policy on the economic system by comparing the equilibria before and after the intervention. This CGE model includes 22 economic sectors (Table 1), including input-output data and energy balance data in the base year of 2002. The model is constructed using the mathematical programming system for general equilibrium under general algebraic modeling system (GAMS/MPSGE) [48] and is solved by using the solver PATH in a one-year time step from 2002 to 2030. The CGE model could provide several indicators of the future macroeconomic trend, and the key indicators include industrial structural change, energy consumption and carbon emissions. An up-to-date technical introduction is available at http://scholar.pku.edu.cn/hanchengdai/imedcge.

The model in this paper divides China into 3 regions of East-, Central- and West China, while international regions are divided into 14 regions (Table 2). The model includes blocks of production, domestic and international trade, and income and expenditure of residents and government. The production activity is represented by the constant elasticity of substitution (CES) function. The inputs are categorized into the material input, energy input, labor input and capital input. In this model, only the energy combustion-related carbon dioxide emissions are considered. The GHGs emissions from other sources such as the production process and land use change are excluded. The technical details of the model have been introduced in Refs. [35–37].

3 Scenarios

This paper aims to estimate the impacts of the US withdrawal from the Paris Agreement on China and India. The impacts include carbon emission pathways, carbon price, and macroeconomic loss. Five scenarios are set up, including the BaU scenario without carbon emissions constraints, and 4 mitigation scenarios.

In the BaU scenario, assumptions are made for the key economic driving forces such as population growth and technology improvements, including the total factor productivity (TFP) improvement and autonomous energy efficiency improvement (AEEI). The setting of the AEEI distinguishes different types of energy carriers and country categories. For instance, the annual AEEI of solid and liquid fuels is set as 1%–2% in the developed countries and 3%–5% in the developing ones; the AEEI of gaseous fuel is 0%–1% in the developed countries and –2% in the developing ones. The negative improvement in the

Table 1 Classification of 22 sectors in the CGE model

No.	Sector	No.	Sector
1	Agriculture	12	Machinery
2	Coal	13	Transport equipment
3	Crude oil and natural gas	14	Electronic equipment
4	Other mining	15	Other manufacturing
5	Food and tobacco	16	Metal product
6	Textile	17	Power generation
7	Paper	18	Manufactured gas
8	Petrol oil	19	Water production
9	Chemicals	20	Construction
10	Non-metal product	21	Transport
11	Metal smelting and processing	22	Service

Table 2 Classification of the regions in the CGE model

Chinese region (3)	Chinese provinces/municipality cities/ autonomous regions (30)
East	Beijing
	Tianjin
	Hebei
	Liaoning
	Shanghai
	Jiangsu
	Zhejiang
	Fujian
	Shandong
	Guangdong
	Hainan
Central	Shanxi
	Jilin
	Heilongjiang
	Anhui
	Jiangxi
	Henan
	Hubei
	Hunan
West	Inner Mongolia
	Guangxi
	Chongqing
	Sichuan
	Guizhou
	Yunnan
	Shaanxi
	Gansu
	Qinghai
	Ningxia
	Xinjiang
International region (14)	**Countries or regions**
AFR	Africa
AUS	Australia-New Zealand
CAN	Canada
CSA	Central and South America
EEU	Eastern Europe
FSU	The Former Soviet Union
IND	India
JPN	Japan
SKO	South Korea
ODA	Other Developing Asia
MEA	Middle East
MEX	Mexico
US	United States
WEU	Western Europe

Note: China's Hong Kong, China's Macao, and China's Taiwan are excluded from the China region due to data unavailability.

developing countries reflects the trend that those countries will transit into more natural gas usage in the coming decades. The AEEI for electricity is 0.5% in the developed countries and 3% in the developing ones. Generally, in the CGE model, the energy consumption and carbon emissions of each country are driven by the complicated mechanism of economic growth, energy efficiency improvements, and relative prices of energy. However, it should be noted that the BaU scenario here is not a current policy scenario since no special mitigation efforts, e.g., the Clean Power Action Plan of the US, are considered. Therefore, the future emissions in the BaU will increase continuously because of economic growth.

On the contrary, in the four mitigation scenarios, it is assumed that the US will withdraw from the Paris Agreement to different extents as follows:

Without scenario (27): In this scenario, the US and other countries will implement their obligation to reduce carbon emissions. The US will reduce its carbon emissions in 2025 by 27% (an average of 26%–28%) from the 2005 levels under the NDC target. Under the 2°C target, the US will achieve the required emission reduction as listed in Table 3.

With scenario1 (20): Compared with the 2005 level, the US only reduces by 20% in 2025 and reaches 4.68 billion ton in 2030. However, other countries have to make additional efforts to reduce more emissions. The addition emissions by the US are allocated as an additional emission reduction burden to other countries based on the population. It should be noted that there are a lot of burden sharing schemes such as per capita convergence, carbon intensity by GDP convergence, abatement cost convergence, or cumulative per capita emissions convergence criterion etc. However, a complete investigation of different schemes is beyond the scope of this paper. The per capita emission convergence approach is chosen since the projection of population of these countries/regions has less uncertainty by 2030 compared with other approaches.

With scenario 2 (13): Compared with the 2005 level, the US only achieves 50% of the NDC target, or reduces by 13.5% in 2025 and reaches 5.25 billion ton in 2030.

With scenario 3 (00): President Trump tries to renovate the traditional energy supply sectors by removing the constraint on coal mining, extraction of crude oil and natural gas, and by investing substantially in infrastructure construction. The emissions in the US will be the same as the 2005 level.

The mitigation scenarios in this paper include the NDC group and the 2°C group. The emissions spaces in each scenario of each region are tabulated in Table 4.

Table 3 Emissions of China, India, and the US in 2030 and cumulative global emissions during 2010–2030 (Gt of CO_2)

Target	Scenario	2030			2010–2030
		China	India	US	Global cumulative emissions
NDC	NDC 27	11.01	5.71	4.11	985.63
	NDC 20	10.92	5.67	4.68	
	NDC 13	10.83	5.62	5.25	
	NDC 00	10.66	5.53	6.33	
2°C	2°C 27	7.75	1.93	3.17	700.21
	2°C 20	7.62	1.89	4.68	
	2°C 13	7.53	1.86	5.25	
	2°C 00	7.36	1.83	6.33	

Table 4 Socio-economic assumptions in the BaU scenario

Region	GDP (billion US$, 2002 constant price)			Population (million)		
	2005	2030	Annual growth rate (2005–2030)/%	2005	2030	Annual growth rate (2005–2030)/%
US	10825	17229	1.88	297	361	0.79
China	1898	9380	6.60	1268	1339	0.22
India	598	4631	8.53	1140	1529	1.18
World	34320	68243	2.79	6444	8223	0.98

During 2010–2030, the global cumulative carbon dioxide emissions are 980 billion ton under the NDC target based on the carbon reduction targets in Ref. [49] and the future gross domestic production (GDP) of each country under the SSP2 scenario [50,51]. While the SSP database of IIASA used for the Fifth Assessment Report provides different emission pathways of each country or region under the 2°C target [51], the 2°C scenario (SSP2-26-SPA0) of the IMAGE model [52] is used for CO_2 emission constraints for each country or region in the 2°C 27 of this paper. In the following sections, the reference scenario is the BaU when mentioning the macroeconomic impacts of carbon reduction. The reference scenario is NDC 27 and 2°C 27 in the NDC and 2°C targets when it comes to the additional macroeconomic impacts from the US withdrawal.

4 Results and discussion

4.1 Carbon emission space change

Figure 1 shows that the energy consumption and carbon emissions in these regions will increase continuously due to the economic growth in the BaU scenario. The CO_2 emissions of the US will increase to 7.3 billion ton in the BaU scenario in 2030 and the annual growth rate is about 1.1%. The carbon intensity reduction rate is about 19.4% (Fig. 2). China has the most GHGs emissions among these three regions. In 2030, CO_2 emissions in China will reach 14 billion ton. The annual average growth rate between 2002 and 2030 is 5.1%.The carbon intensity decreases by 36.8% over 2002–2030 periods (Fig. 2), which is far less than the NDC target of 60%–65%. China needs to make additional efforts to achieve its NDC target. In India, CO_2 emissions are lower than that of the US and China, up to 6.0 billion ton and the annual growth rates are about 6.2% from 2002 to 2030. Their emissions growth rates are lower than those in China due to the lower GDP growth. Overall, the growth rates of carbon emission are lower than that of GDP growth rates, implying that the economy is developing in a decarbonization manner.

The US withdrawal from the Paris Agreement will have impacts on the emission spaces in the US, China, and India. The US withdrawal will lead to an increase of its own emission space by 14%, 28%, and 54% in the NDC 20, NDC 13, and NDC 00 scenarios in 2030 (Fig. 3). However, China and India will have to reduce more CO_2 emissions by 0.8%, 1.6%, and 3.2% in the NDC 20, NDC 13, and NDC 00 scenarios. While under the 2°C target, compared with full implementation of its obligation in the 2°C 27 scenario, the US will get more additional emission spaces of about 48%, 66%, and 100% in the 2°C 20, 2°C 13, and 2°C 00 scenarios. The additional reduction rate in the 2°C 20, 2°C 13, and 2°C 00 scenarios will be 1.7%, 2.8%, and 5.0% in China and 1.7%, 2.9%, and 5.1% in India (Fig. 3), respectively.

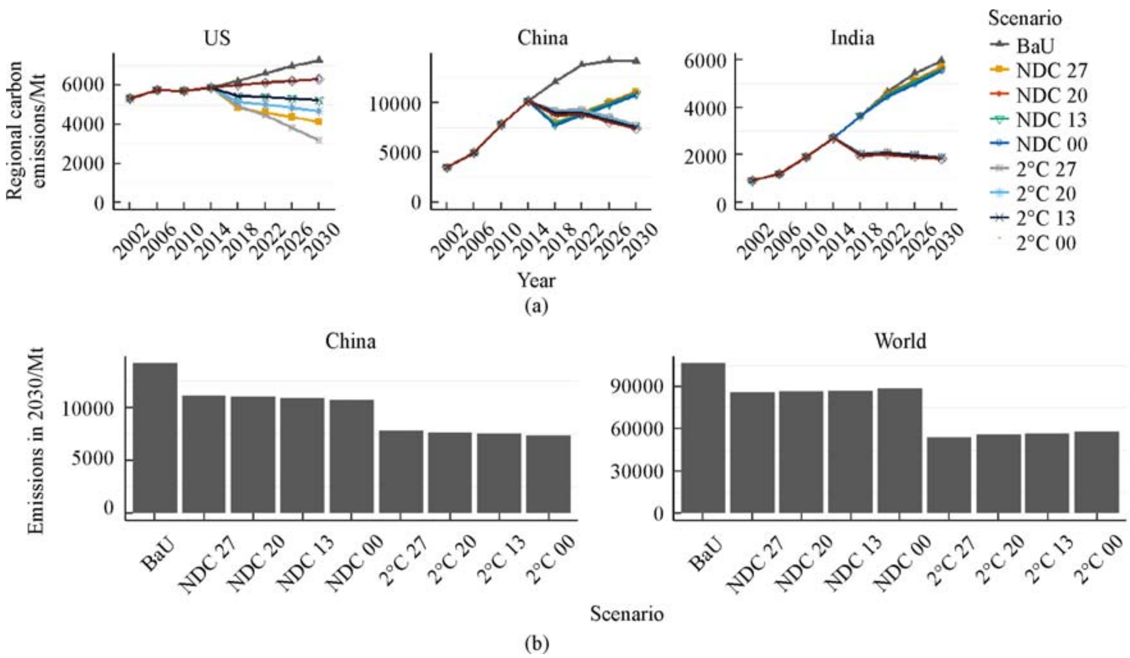

Fig. 1 Carbon emission trajectories in different scenarios
(a) 2002–2030; (b) Global and China's emissions in 2030

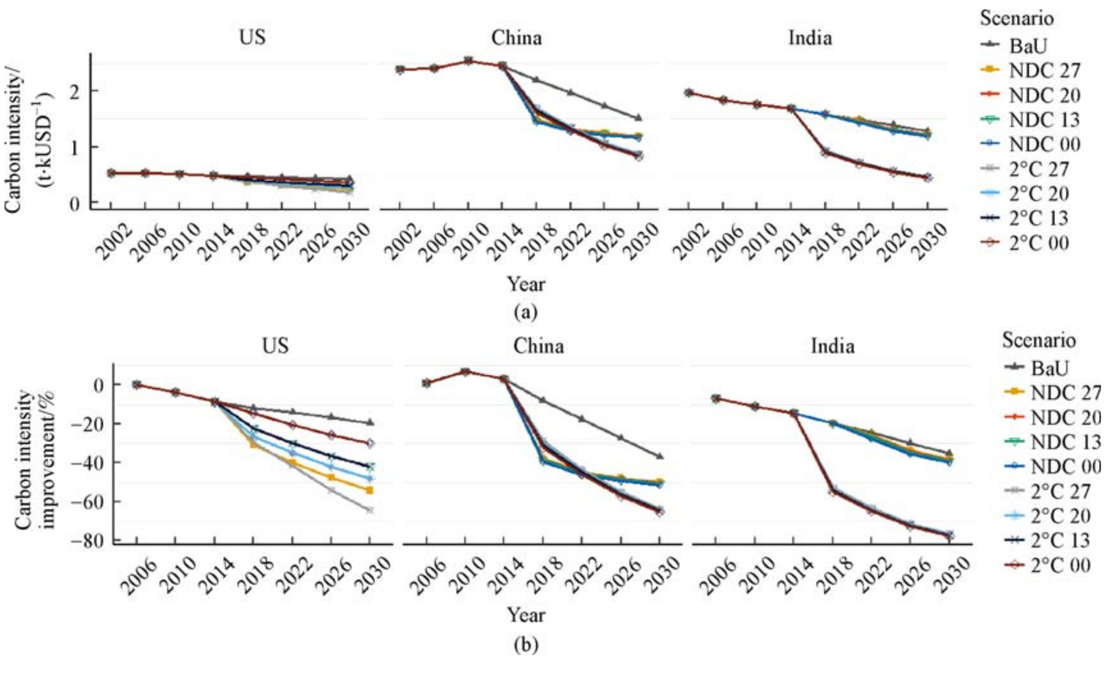

Fig. 2 Carbon intensity and carbon intensity improvement from the 2002 level
(a) Carbon intensity; (b) carbon intensity improvement from the 2002 level

4.2 Impact on carbon price

Figure 4 demonstrates the carbon price in each region in different scenarios. The carbon reduction in the US will have impacts on the carbon price in other regions significantly. In the NDC 27 scenario, the carbon price of the US is the highest, about US$136/t in 2030, whereas the carbon price will fall to US$90/t, US$59/t and US$20/t in the NDC 20, NDC 13, and NDC 00 scenarios, respectively. The US withdrawal will lead to the carbon price reduction in the US. However, other regions will have a higher carbon price. For example, the carbon price in China will

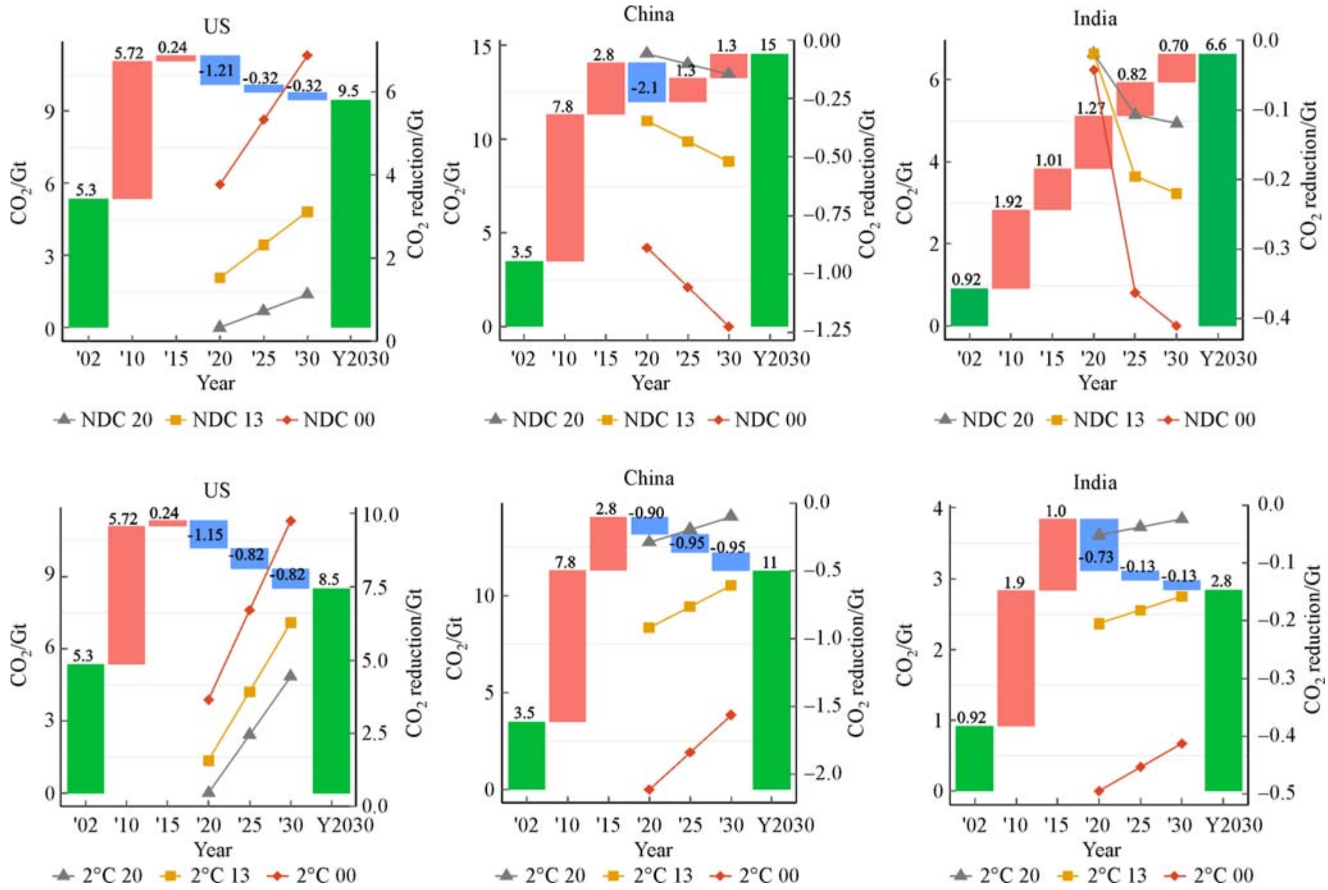

Fig. 3 Carbon emission in the BaU scenario (bar, left axis) and carbon emission reduction from BaU level (line, right axis)

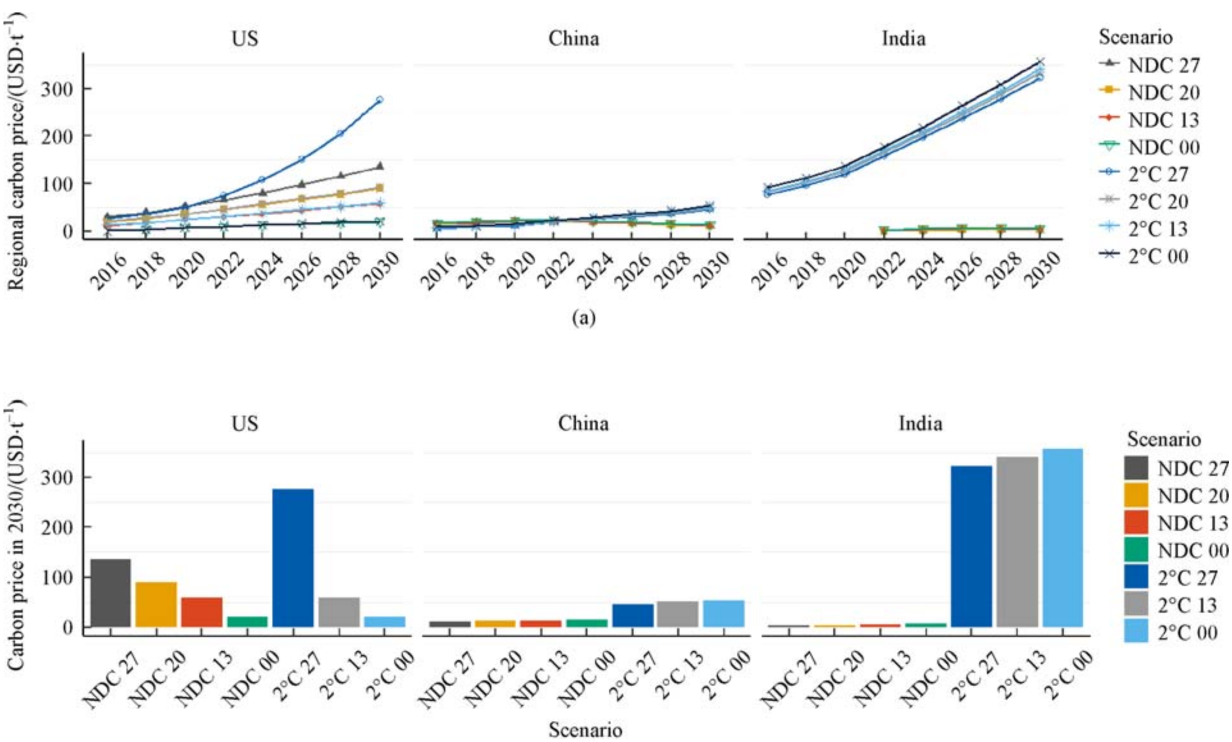

Fig. 4 Carbon price in achieving NDC and 2°C targets (2002 constant price)
(a) 2016–2030; (b) in 2030

increase from US$23/t in the NDC 27 scenario to US$24/t in the NDC 20, US$25/t in the NDC 13, and US$28/t in the NDC 00 scenarios, which is equivalent to an additional expenditure on carbon reduction of US$12 billion, US$25 billion, and US$50 billion, respectively. In India, the carbon price will increase from US$3.5/t in the NDC 27 scenario to US$4.2/t, US$4.9/t, and US$6.5/t in 2030 in the NDC 20, the NDC 13, and the NDC 00 scenarios, respectively, which is equivalent to an additional expenditure on carbon reduction of US$4.7 billion, US$9.5 billion, and US$19.2 billion, respectively.

Each country will face a scarcer carbon emission allowance under the 2°C target. The carbon price in the US in 2030 will reduce from US$277/t in the 2°C 00 scenario to US$21/t in the 2°C 00 scenario, which is equivalent to a carbon expenditure saving of US$1.6 trillion in 2030 (Fig. 5). For other regions, the carbon price and expenditure will increase substantially. China's carbon price in 2030 will increase from US$93/t in the 2°C 27 scenario to US$108/t in the 2°C 00 scenario, equivalent to an additional carbon expenditure of US$87 billion. In India, the carbon price in 2030 will increase from US$323/t to US$357/t in the 2°C 00 scenario, which is corresponding to a more carbon expenditure by US$36 billion (Fig. 5).

4.3 Macroeconomic impacts

The macroeconomic impact of carbon reduction is represented by the GDP change between the intervention scenarios and reference scenarios. Policy intervention leads to the mitigation cost. The US withdrawal from the Paris Agreement will lead to a higher carbon price in other countries. They need to make more carbon reduction efforts to achieve the mitigation targets. Figures 6 and 7 show the additional GDP loss to achieve mitigation target in these regions. If the US achieves its NDC target, its GDP loss would be US$103 billion (US$285/capita), accounting for 0.6% of GDP. However, if the US withdraws from Paris Agreement, the loss will decrease by US$41 billion, US $67 billion and US$93 billion in the NDC 20, NDC 13, and NDC 00 scenarios, which is equivalent to the per capita GDP of US$113, 187 and US$258/capita, respectively.

Compared with the BaU scenario, China's GDP loss under the NDC 27 scenario is US$127 billion, about 1.56% of the GDP (95 per capita) in 2030. The GDP loss in China is much higher than that in the US. The GDP loss will increase to US$146 billion (an additional per capita GDP loss US$15/capita) in the NDC 00 scenario. In India, the GDP loss is US$4.3 billion (per capita GDP loss of US

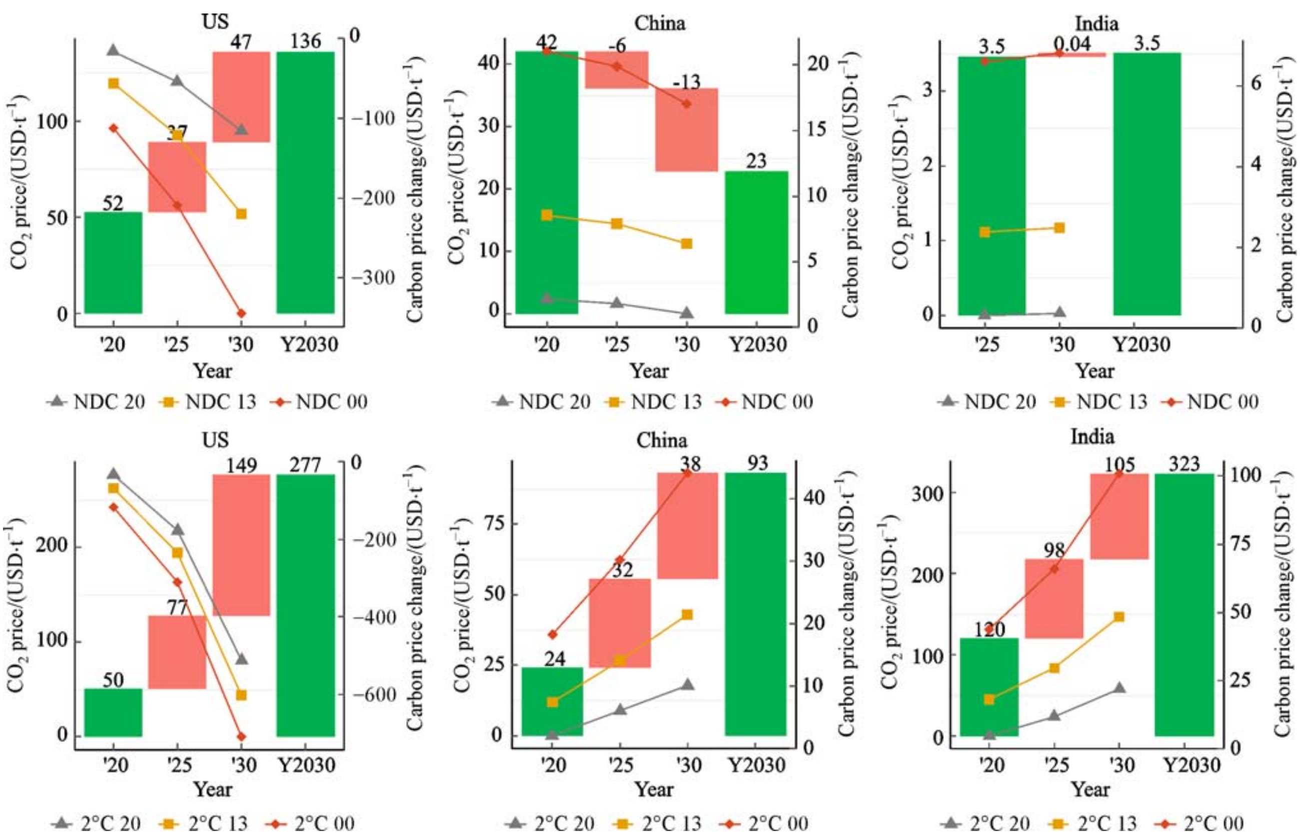

Fig. 5 Carbon price in full implementation of the US obligation scenario (bar, left axis) and carbon price change compared with full implementation scenario (line, right axis) in achieving NDC and 2°C targets (2002 constant price)

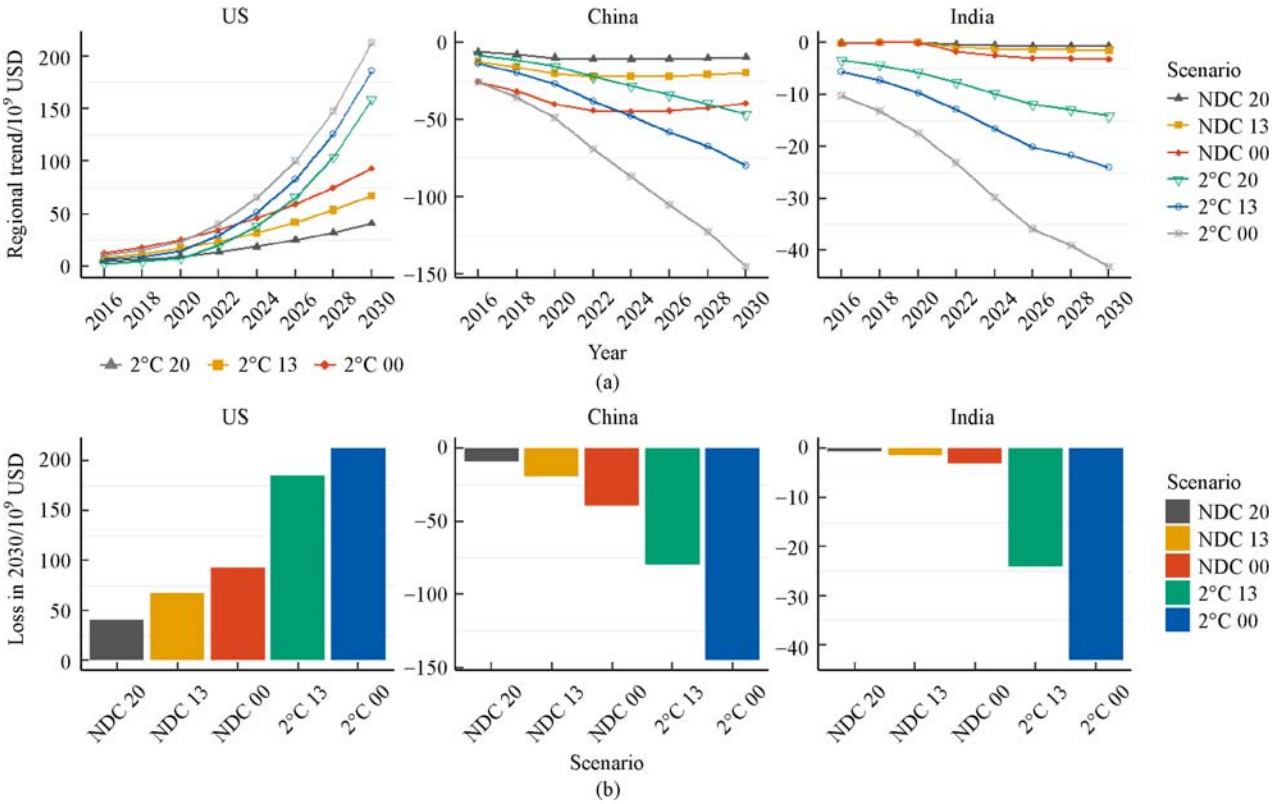

Fig. 6 Additional GDP loss under NDC and 2°C targets compared with full implementation of the US obligation scenario (measured in USD, 2002 constant price)

(a) 2016–2030; (b) in 2030

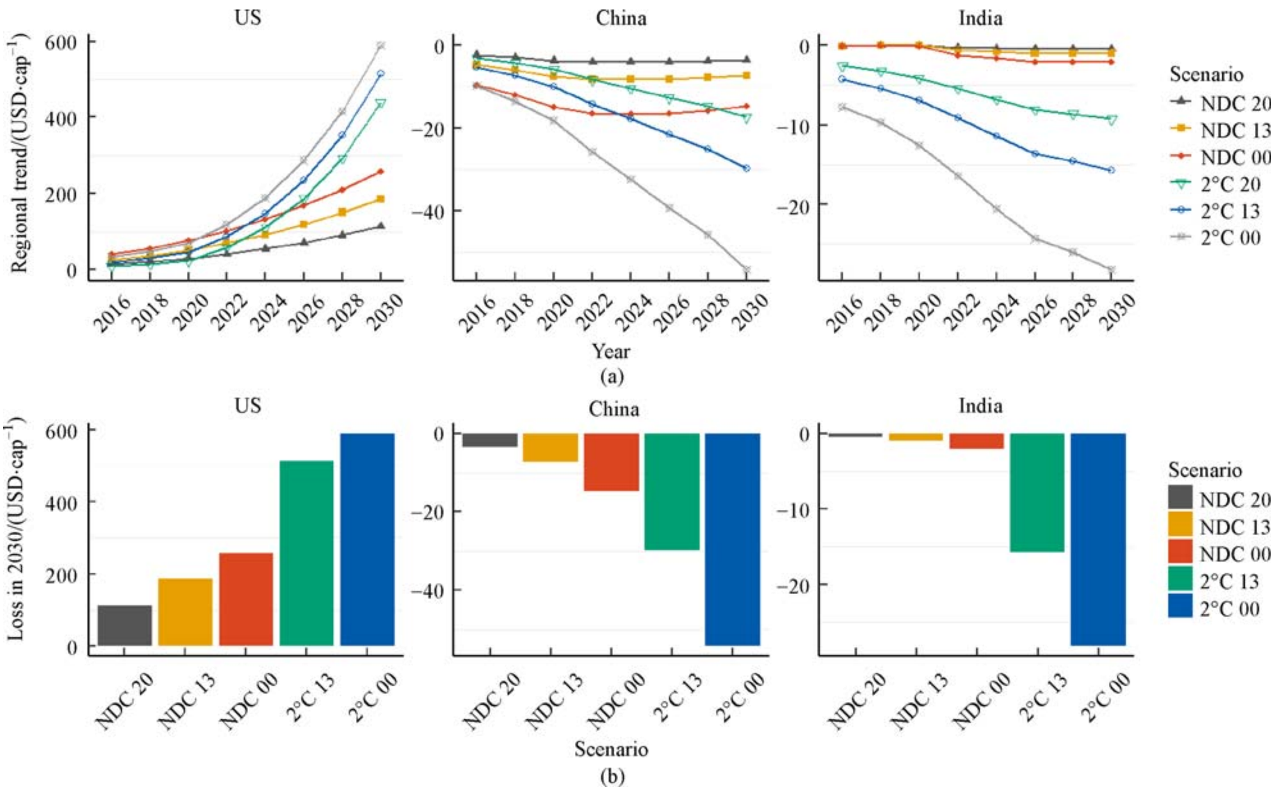

Fig. 7 Additional per capita GDP loss under NDC and 2°C targets compared with full implementation of the US obligation scenario (measured in USD, 2002 constant price)

(a) Per capita GDP loss during 2016–2030; (b) per capita GDP loss in 2030

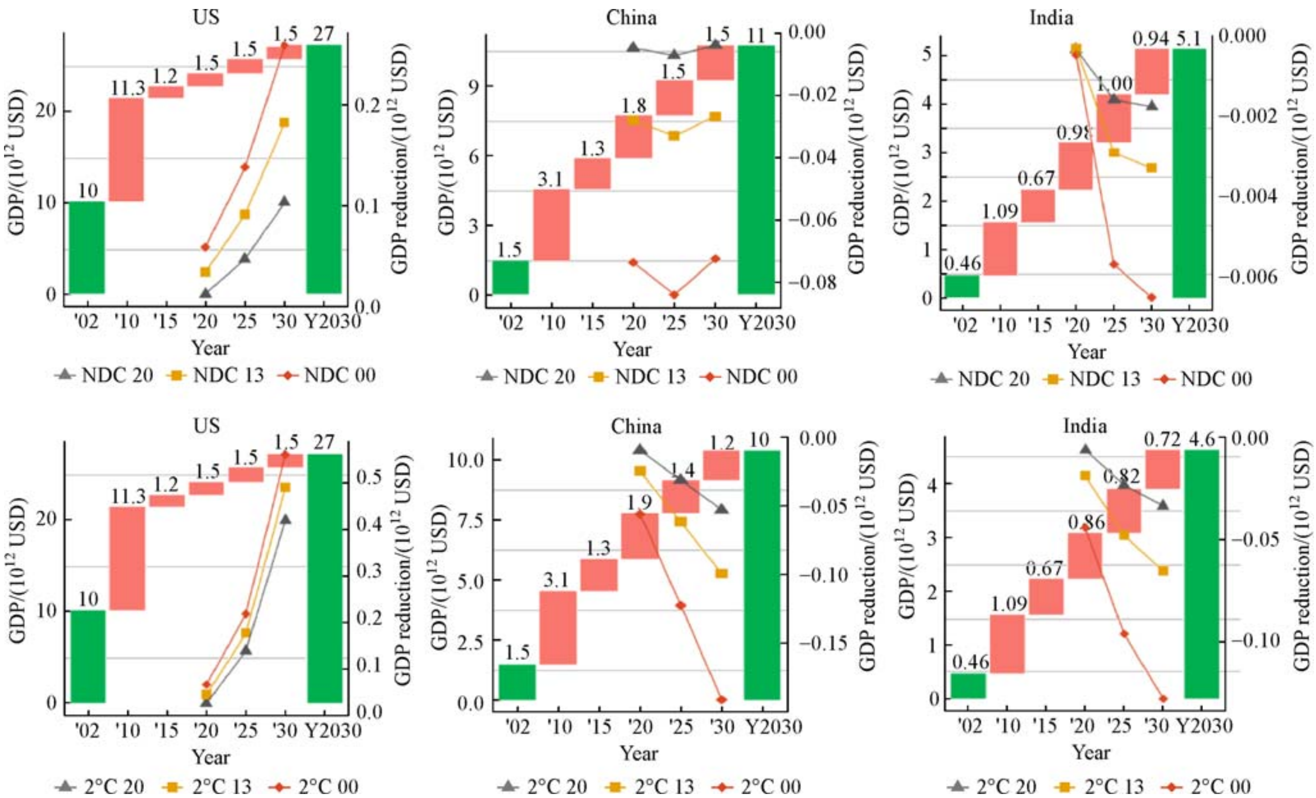

Fig. 8 GDP in BaU scenario (bar, left axis) and additional GDP loss (line, right axis) under NDC and 2°C targets compared with full implementation of the US obligation scenario (measured in USD, 2002 constant price)

$2.9/capita) in 2030 under the NDC 27 scenario, equivalent to 1.53% of the GDP, while in the NDC 00 scenario, the additional loss will be US$3.1 billion (per capita GDP loss of US$2.1/capita) (Figs. 8 and 9).

Under the 2°C target, the GDP loss of the US will be US $212 billion in the 2°C 27 scenario, accounting for 1.23% of the GDP, whereas the GDP loss will drop to US$53 billion, US$26 billion and US$−1.1 billion in the 2°C 20, 2°C 13, and 2°C 00 scenarios, about 0.31%, 0.15% and −0.01% of the GDP, respectively. The results indicate that the GDP even increases slightly in the 2°C 00 scenario in the US, because a lower carbon price makes its industrial products competitive in the global market. It will lead to a higher GDP growth. However, other countries will have a more GDP loss. For example, the GDP loss from carbon reduction in China in 2030 will be US$441 billion (US $329/capita) and 4.7% of the GDP in the 2°C 27 scenario, while the GDP loss will increase to US$513 billion (accounting for 5.7% of the GDP) in the 2°C 00 scenario. In India, the GDP loss will increase from US$510 billion (US$334/capita, or 10.9% of the GDP) in the 2°C 27 scenario to US$553 billion in the 2°C 00 scenario in 2030. The per capita GDP loss will increase US$28.2/capita.

4.4 Discussion

This paper assesses the impacts of the US withdrawal from Paris Agreement on the US, China and India by using the CGE model. The impacts include carbon emissions, carbon price, and economic impact. The results suggest that the US will bring benefit only in the US, but bring additional burden for other countries, if the US withdraws from the Paris Agreement while other countries still fulfill their mitigation target. The results also demonstrate that compared with the NDC scenario, the impact of the US withdrawal is much higher under 2°C targets. The carbon price obtained in this paper is also compared with that obtained from the IMAGE model [52]. As Table 5 shows, the prices of both models are quite close, as far as the US is concerned, which are US$40–50/t in 2020. However, the carbon price obtained in this paper is increasing much faster than that obtained from the IMAGE model for the US and India toward 2030. For China, the carbon price from the estimation is lower than that of the IMAGE model, because large-scale penetration of low-carbon technologies are not considered, such as non-fossil fuel, carbon capture and storage, and negative emission technology in the model. The carbon price and GDP loss are probably overestimated in this paper. If considering the fact that the low-carbon technology will penetrate in the market in the future, the carbon price will be lower than the estimation in this paper. Only combustion-related carbon emissions are included in the model and emissions from other sources are excluded such as the industrial produc-

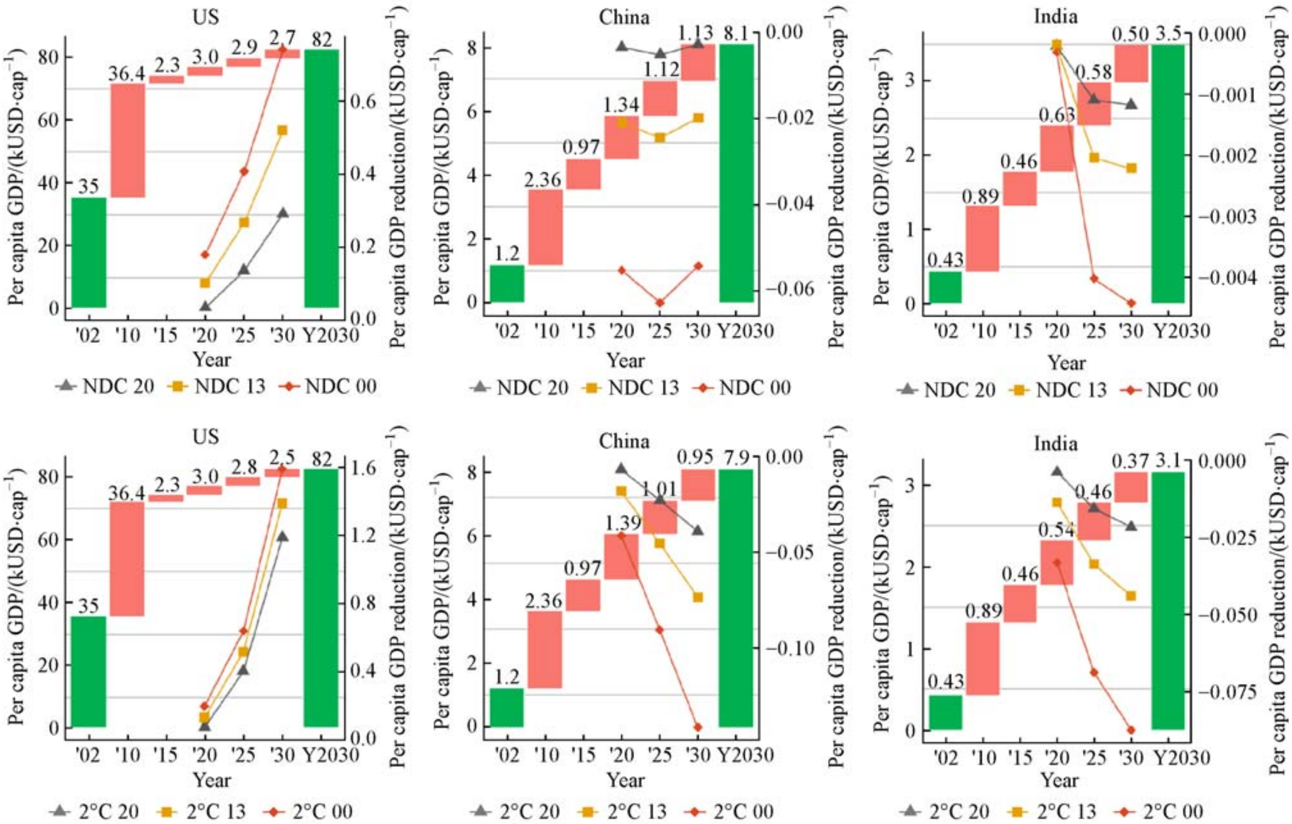

Fig. 9 Per capita GDP in the BaU scenario (bar, left axis) and additional per capita GDP loss (line, right axis) under NDC and 2°C targets compared with full implementation of the US obligation scenario (measured in USD, 2002 constant price)

Table 5 Comparison of carbon price under the 2°C scenario between the result in this paper and that from the IMAGE model

Result	Country	2020	2030
This paper	China	95.19	322.01
	India	160.3	421.5
IMAGE	China	42.62	117.97
	India	41.25	115.12

tion process and land use related emissions. All carbon reduction must be achieved within the energy system, which will lead to a higher carbon price as well. The carbon constraints are imposed on each country in this model while a global carbon emission constraint is imposed in the IMAGE model. Therefore, there is only an identical global carbon price in the IMAGE model. An implicit implication is that full global scale carbon emission trading is implemented among all countries, which is helpful to reduce the carbon price.

At the same time, the macroeconomic costs in this paper should be interpreted cautiously. This paper only captures the cost of carbon reduction while ignoring the benefits it will bring about. For instance, through carbon reduction, there will be substantial co-benefits of reducing air pollutants emissions, improving the human health, and saving resource consumption. Air pollutants reduction is also co-beneficial for the plant, the forest, the ecosystem, and even for solar PV generation. If taking into consideration the co-benefits from air quality improvement, the actual GDP loss would be lower. Nevertheless, the current simulation is still helpful to judge the general macroscopic situation.

The carbon price is a shadow price, a highly theoretical instrument in a CGE model that helps to change the relative prices of inputs and bend the curves of economic and energy trends to meet the exogenous targets. In reality, the mechanism of such impacts on macroeconomy is much more complicated than that modeled in the current ex-ante model such as CGE. First of all, a lot of other factors that are not reflected in ex-ante models play a more important role in determining production and investment decisions.

In addition, as pointed out in Ref. [53], there is a perception that there is a trade-off in short- to medium-term between economic growth and climate action, but this is due largely to a misconception (built into many model-based assessments) that economies are static, unchanging and perfectly efficient. Any reform or policy which forces an economy to deviate from this counterfactual incurs a trade-off or cost. Therefore, any climate policy is often found to impose large short- and medium-term costs. In reality, however, there are a number of reform opportunities that can reduce market failures and rigidities that lead to the inefficient allocation of resources, hold back growth, and generate excess GHG emissions.

It is uncertain how much the US withdrawal will affect the real market and states due to many factors. First of all, low-carbon technologies become cost competitive against conventional technologies. After one year in office, it is becoming increasingly clear that all the measures envisioned and, in part, implemented by the current administration of the US are unable to reverse fundamental, market-driven demand-side trends: natural gas remains cheaper than coal, something that removing restrictions on mining cannot change. In global markets, car manufacturers cannot afford to build only due to loose regulations in one country — given hard phase-out mandates for new internal combustion engine vehicles in a growing number of jurisdictions, even the US manufacturers continue to expand their investments in the electric drivetrain technology, further bringing down the technology cost. Second, the federal government has only limited powers on matters related to the choice of energy sources: it is, therefore, a common misperception abroad that the US federal policy will have far-reaching impacts on the US GHG emissions, when in reality states and even municipalities have much more important legislative and executive powers.

The climate policy of the Trump Administration has led to an additional uncertainty for global climate governance. Although this paper projects that if the reduction burden is allocated to the other countries, their mitigation costs would increase, and it is not necessary to look it from such a pessimistic perspective. On the contrary, it could be an opportunity for China to enhance its soft power to fill the power vacuum left by the US and play a more active role in global climate governance. Domestically, China should reach the high ends of its climate targets of the current NDC to peak CO_2 emissions and to decrease the carbon intensity of per unit of GDP by 65% below 2005 levels before 2030. On the other hand, internationally, China should respond to the leadership call by rebuilding a shared and collective leadership that includes China, the EU, India, Brazil, and South Africa. Moreover, encouraging all countries to keep their efforts is in compliance with the interest of China and India since if the carbon reduction burden is shared by more countries, the reduction cost will be noticeably lower.

5 Conclusions

This paper accesses the carbon emission spaces, carbon price, and economic impact on the US, China, and India because of the US withdrawal from the Paris Agreement recently. The findings show the global cumulative carbon emissions are constant and the burden sharing scheme among countries is fixed. The US withdrawal could get an additional carbon emission space and a lower carbon price in the US. However, the emission space in other regions will be reduced and additional macroeconomic costs will be increased. The US withdrawal will lead to a significant change in the Paris Agreement implementation and global climate governance.

The US withdrawal will win itself more carbon emission quota, but it will reduce the quota for other regions to achieve mitigation targets. For example, under the NDC target in 2030, the US withdrawal will lead to more reductions of CO_2 emissions by 0.8%, 1.6%, and 3.2% in NDC 20, NDC 13, and NDC 00 in China. The carbon price will rise by US\$3.7–15/t in China. The additional GDP loss will be US\$9.5–39 billion in the NDC 20, the NDC 13, and the NDC 00 scenarios. India will suffer a lower impact than China. In India, CO_2 emissions also decrease by 0.8%, 1.6%, and 3.2% in the NDC 20, the NDC 13, and the NDC 00 scenarios. The carbon price will increase by US\$0.7–3/t. The additional macroeconomic loss is about US\$0.7–3.1 billion in 2030 in India.

Under the 2°C target, the US could gain more emission spaces by 48%, 66%, and 100% in 2°C 20, 2°C 13 and 2°C 00 compared with a full implementation of its obligation in the 2°C 27 scenario. The carbon reduction rate of China will increase by 1.7%, 2.8%, and 5.0%. The carbon price will rise by US\$14–45/t in China. The additional GDP loss will be US\$47–145 billion in China. The carbon reduction rate in India will increase 1.7%, 2.9%, and 5.1%. The carbon price will rise by US\$10.7–33.9/t in India. The additional macroeconomic loss is about US\$14–43 billion in India.

Climate change is a great threat to all countries. As the biggest developed country, the US withdrawal from Paris Agreement will add burden to other countries, especially to China and India. China and India are developing countries with the largest population. Climate mitigation will bring negative impact on the economy and welfare of the people in the two countries. The US withdrawal will exacerbate the negative impact on the two countries. It will also have unpredictable impacts on the implementation of climate mitigation in other countries. However, it is also a good opportunity for China and India to enhance their soft power to fill the power vacuum left by the US and play a more active role in global climate governance, through achieving the high ends of their NDC commitment and rebuilding a shared leadership with other main countries.

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