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Estimation of Greenhouse Gas Emissions from the EU, US, China, and India up to 2060 in Comparison with Their Pledges under the Paris Agreement

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Received: 24 June 2017; Accepted: 2 September 2017; Published: 6 September 2017

Abstract: A greenhouse gas (GHG) emission model was developed based on economic and energy sector development at the national level. Different development scenarios were established, including BAU (scenario with business as usual) and API (scenario with additional policy interventions). We simulated annual GHG emissions under different scenarios for the EU, US, China, and India from 2016 to 2060, and evaluated the impacts of emission changes on their mitigation pledges (Intended Nationally Determined Contributions, INDCs). Two main conclusions were obtained. (1) In API, EU's emissions fell from 4160 to 2340 $MtCO_2e$/year and would probably achieve its INDC pledge. Though US's emissions fell from 6330 to 4020 $MtCO_2e$/year, it still had a deficit of 370 $MtCO_2e$ in 2025. If the Clean Power Plan (CPP) is abandoned, US's emissions would remain above 6000 $MtCO_2e$/year. (2) In BAU, China's emissions peaked in 2044 while India's emissions were already close to the strict INDC target. In API, China and India both achieved a reduction of about 2000 $MtCO_2e$ exceeding their INDC targets in 2030. Chinese emissions peaked in 2030, but Indian emissions grew until 2060. This study also indicates that developed countries should play a more important role in future mitigation efforts.

Keywords: GHG emission; low-carbon planning; energy structure; INDCs

1. Introduction

The Paris Agreement was reached at the end of 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), and entered into effect in November 2016. The long-term goal of the Paris Agreement is to hold the increase in global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the increase to 1.5 °C, which would significantly reduce the risks and impacts of climate change. The Paris Agreement does not enforce national greenhouse gas (GHG) emission reductions; rather, countries are encouraged to submit their emission targets in the form of Intended Nationally Determined Contributions (INDCs). INDC emission pledges will be evaluated every five years, and more ambitious targets may be established in the future. However, the potential changes in future emissions at the national level under national policy interventions are poorly understood and their capacity to meet INDC mitigation targets under the Paris Agreement is still unknown.

Prior to this study, 197 parties had submitted their INDCs to the UN and had proposed their future emission targets. However, Rogelj et al. [1] reviewed ten studies and found that global emissions, in accordance with INDC scenarios, would result in a global temperature rise of 2.6–3.1 °C by the end of the century, i.e., clearly greater than the targeted 2 °C threshold. Therefore, to achieve the 2 °C (or 1.5 °C) target, it is necessary to strengthen national mitigation efforts. Some studies have evaluated national INDC targets. For example, Greenblatt and Wei [2] evaluated the US INDC target, and found that, although the current US mitigation policies are expected to be implemented continuously, they are unlikely to meet the INDC commitment target for 2025. Dai et al. [3] evaluated China's mitigation commitment for 2020, and reported that the current policy was not sufficient to support the 2020 INDC target. Climate action tracker (CAT) estimated emission changes under future policy interventions in some countries, and evaluated their impact on the achievement of temperature targets [4].

This study estimated national GHG emissions in the next few decades based on the implementation of policies and mitigation plans from the EU, US, China, and India. National GHG emissions were linked to social and economic development thus a dynamic model of emissions from fuel combustion was developed based on the final energy sector. We first simulated annual GHG emissions under different policy scenarios in the future, and then examined the emission changes in response to mitigation polices, and evaluated their impacts on national INDC emission pledges.

2. Materials and Methods

2.1. Carbon Dioxide (CO_2) Emission Model Based on Final Consumption by Sector

About 86% of global CO_2 emissions originate from fossil fuel combustion [5,6], which is closely related to energy production and human society, and is therefore affected by socioeconomic development and the structure of energy production. The Kaya identity is a concise formula that describes this relation. It decomposes CO_2 emissions into four factors: human population, GDP per capita, energy intensity (energy consumptions per unit of GDP), and CO_2 intensity (emissions per unit of energy consumed) [7]. This decomposition is used in IPCC assessment reports to evaluate the drivers of emissions [7,8]. And some extended Kaya identities have been developed to investigate the special sectors' contribution [9,10]. However, the drivers of the Kaya identity are proximate, and it is difficult to quantitatively assess the policy implications [11]. Thus, based on the Kaya identity, we conducted a further decomposition, which first calculated the final consumption by sector from the value added and energy intensity, then converted it to total primary energy supply (TPES) by multiplying it with energy efficiency coefficients, and finally determined the CO_2 emission from fossil fuels in the TPES. The computation formula is as follows:

$$CO_2 = \left(\sum GDP \times EI_i(GDP, Po)\right) \times \begin{vmatrix} FE_f \\ FE_p \\ FE_r \end{vmatrix}^T \times \begin{vmatrix} F_f & F_p \times TE_f & 0 \\ 0 & N_p \times TE_n & 0 \\ 0 & H_p \times TE_h & 0 \\ 0 & G_p \times TE_g & G_r \\ 0 & S_p \times TE_s & S_r \\ 0 & B_p \times TE_b & B_r \end{vmatrix}^T \times \begin{vmatrix} \sum PE_j \times CC_j \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix} \quad (1)$$

In Formula (1), Po is population; EI_i is energy intensity by sector (i: agriculture, industry, service, household, and others); and FE in the left matrix is the percentage of final consumption by energy sector (subscript f for fossil, p for power, and r for renewable). The middle matrix represents energy efficiency coefficients, in which the first and third columns are the ratios of TPES/final energy consumption for fossil fuels (F_f), geothermal (G_r), solar and wind (S_r), and biofuels and waste (B_r). The second column refers to the process of power generation, where Xp is the share of power generation for energy X and TE_x is the reciprocal of thermal efficiency for energy X (X: F for fossil, N for nuclear, H for Hydro, G for geothermal, S for solar and wind, and B for biofuels and waste). PE_j and CC_j in the right matrix are the share of fossil fuels in TPES and their CO_2 intensity (j: coal, crude oil, and natural gas). In the model, GDP is in purchasing power parity (PPP) units, since it takes the exchange rates among different regional markets into account, which has been proved to be a better indicator to describe the relationship between energy and the economy [12,13].

The CO_2 emissions can be calculated when all variables in Formula (1) are known for given years. To address climate change and pursue sustainable development, more than 190 parties have established policies relating to socioeconomic development and energy production. For example, the Chinese government expects to reach a peak population of 1.45 billion around 2030, which will then fall to 1.38 billion in the mid-21st century [14], and the share of coal in the TPES will fall to 62% in 2020 [15]. To estimate the continuous variation of emissions in the future, a time series of all variables is needed and should be considered alongside the planned value for target years. We established two scenarios. One extends the current case (business as usual, BAU), while the other is with additional policy interventions (API). We used three methods to obtain data for these scenarios.

Method 1 used forecasts from international organizations. Population data was obtained from the World Population Prospects (WPP) [16] provided by the UN, and GDP was obtained from long-term forecasts made by the Organization for Economic Cooperation and Development (OECD) [17], and revisions were made if there were official plans available. For example in China, the population projected by the government is in accordance with the average values of the high and medium fertility variant scenarios simulated by the WPP, and the GDP growth rate reported by the OECD is promoted to be maintained in the 13th Five-Year Plan, which aims to double the GDP in 2020 compared to 2010. The GDP forecast by the OECD is mainly based on an assessment of the economic climate in individual countries and the world economy [17], where the impact of addressing global warming may not be totally accounted for. By considering the relationships between reduction targets and abatement costs [18–20], we found that the OECD forecast takes 20–80% of the GDP loss into account, in which the higher loss values were for developed countries and the lower loss values were for developing countries. The OECD GDP projections from 2020 to 2060 were adjusted with abatement cost curves for the different countries [18–20], and then used for two scenarios.

Method 2 fixed the intercept at the target year by logistic curve fitting, and was mainly used in API. For example, as mentioned above, the share of coal in the TPES for China is projected to fall to 62% in 2020 [15] and to further fall below 40% in the mid-21st century [21,22], which represents 66% of the 2014 value according to energy balance data from the International Energy Agency (IEA) [23]. Here, logistic growth functions that were constrained to cross the given points in different target years were fitted to simulate the change in the share of coal in the TPES over time (Figure 1). Variables such as the share of natural gas in the TPES, energy intensity by sector, and the proportion of power generated by clean energies were also calculated by this method, with reference to the Energy Technology Perspectives [24,25] and national-level energy development strategies [15,21,22,26–35] to set the targets in designated years.

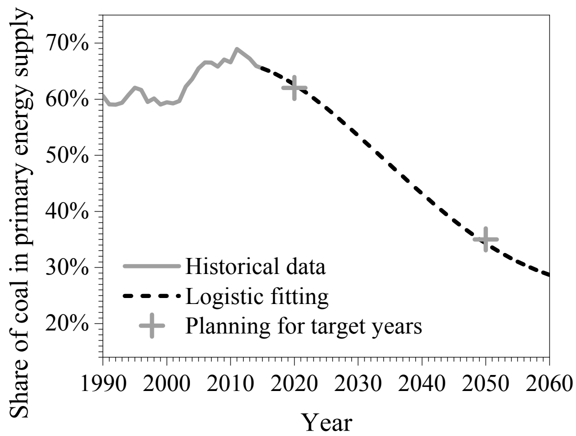

Figure 1. Projecting the share of coal in the future primary energy supply by fixing the intercept at the target year for a logistic curve.

Method 3 was an extrapolation of the energy-economy relationship, and was mainly used in BAU. Studies have shown that a structural shift in the value added from agriculture to industry to services, and sector shifts in the final energy use of residential areas, industry, agriculture, and services have a significant statistical relationship with economic growth [12,13]. Based on World Development Indicators for the period of 1960–2015 from the World Bank [36] and energy balance data for the period of 1974–2015 from the IEA [23], we found that such nonlinear relationships also existed among energy intensity by sector, energy conversion efficiency, and economic growth. It is therefore possible to predict the changes of these energy-related variables in the future if the development pattern remains the same as that during the past several decades. Table 1 shows the fitted functions of related variables, whose p-values were all lower than 0.01 level and were valid for predicting the trend over the next few decades.

Table 1. Parameterized functions of the variables in the emission model.

Variables	Available Regions	Functions [1]	Explained Variance
Share of agriculture in GDP	World	$y = 1 - Gp\hat{}0.886/(619\hat{}0.886 + Gp\hat{}0.886)$	0.924
Share of service in GDP	World	$y = \mathrm{Arctan}(Gp \times 1.83 \times 10^{-4}) \times 0.814/(\mathrm{Pi}/2)$	0.685
Final energy intensity of agriculture [2]	Developing countries of Europe and Central Asia and China	$y = (0.0033 + 0.0207 \times Gp)\hat{}(-1/1.23)$	0.974
	Others in the world	$y = 4.41 \times (1 + Gp)\hat{}(-0.209)$	0.728
Final energy intensity of industry	Developing countries of South Asia, Africa and Latin America	$y = 49.1 \times (1 + Gp)\hat{}(-0.286)$	0.862
	Others in the world	$y = (6.22 \times 10^{-5} + 6.13 \times 10^{-4} \times Gp)\hat{}(-1/1.38)$	0.952
Final energy intensity of service	Europe and developing countries of Central Asia	$y = 44.8 \times (1 + Gp)\hat{}(-0.436)$	0.510
	Other developing countries	$y = 1/(33.0 \times Gp\hat{}(1.00175 - 1) - 32.8)$	0.554
	Developed countries of America	$y = 935 \times (1 + Gp)\hat{}(-1.17)$	0.953
Final energy intensity of household	World	$y = 1/(0.00656 \times Gp\hat{}(1.73 - 1) - 0.00186)$	0.933
Final energy intensity of others	World	$y = 1/(0.242 \times Gp\hat{}(1.39 - 1) - 0.0974)$	0.656
Share of non-energy use in final consumption	World	$y = 0.126 - 0.126/(1 + (Gp/4.64)\hat{}0.944)$	0.596
Share of electricity and heat in final consumption	World (excl. Middle East)	$y = 0.0475 \times Gp\hat{}0.0574$	0.691
Ratio of fossil/clean energy in final consumption	World (excl. Middle East)	$z = (Gp - 14)/13, y = 35.9 \times \exp(1 - \exp(-z) - z)$	0.470

[1] y for dependent variable and Gp (GDP per capita, KUSD at 2005 PPP) for independent variable. [2] Unit of energy intensity is toe/MUSD at 2005 PPP.

2.2. Non-Fossil CO_2 GHG Emissions Data

Non-fossil CO_2 GHGs account for about one third of the total GHG emissions [8], but there is no detailed global dataset for these emissions that could be used to develop a model such as that developed for CO_2 in this study. Here, representative concentration pathway (RCP) simulations for individual countries provided by the C-ROADS model [37] were used to account for the emissions of non-fossil CO_2 GHGs. On the basis of our assumptions, RCP 8.5 was in accordance with BAU and RCP 4.5 was in accordance with API.

3. Results and Discussion

Figure 2 shows the GHG emission results for China, EU, US, and India simulated by the methods above, and their comparisons with INDC targets (Table 2), respectively. The INDC symbols in Figure 2 were calibrated to emissions without taking Land Use, Land-Use Change and Forestry (LULUCF) into consideration [4]. The uncertainty intervals were calculated by the nonlinear average growth of errors in the logistic map [38].

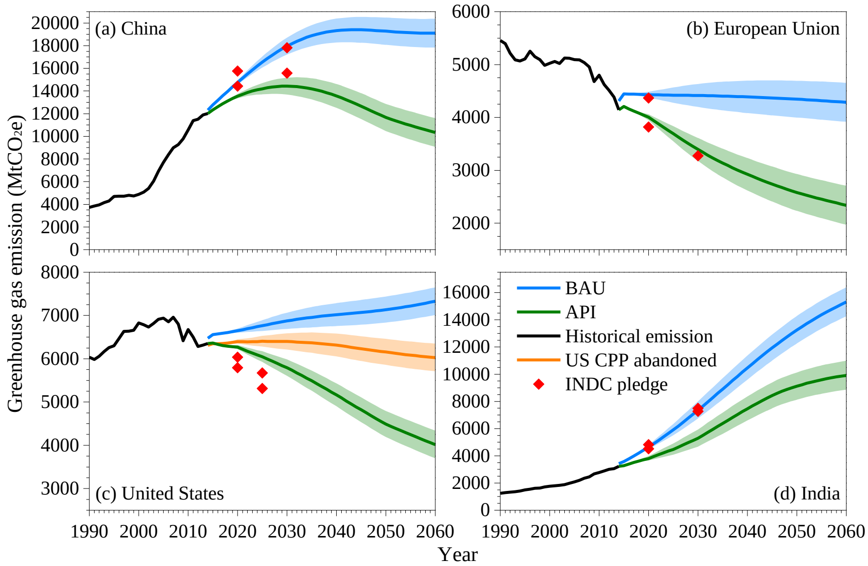

Figure 2. Greenhouse gas (GHG) emissions of BAU and API in comparison to the Intended Nationally Determined Contributions (INDCs).

Table 2. Energy and emission related Intended Nationally Determined Contributions (INDCs) of China, EU, US, and India.

Countries	2020 Targets	2025 or 2030 Targets
China	40–45% emissions reduction per GDP below 2005 levels; non-fossil share of energy supply to 15%	60–65% emissions reduction per GDP below 2005 levels; non-fossil share of energy supply to 20%
EU	20–30% emissions reduction below 1990 levels	40% emissions reduction below 1990 levels
US	17% emissions reduction below 2005 levels	26–28% emissions reduction below 2005 levels
India	20–25% emissions reduction per GDP below 2005 levels	33–35% emissions reduction per GDP below 2005 levels; non-fossil share of cumulative power generation capacity to 40%

3.1. China

In China, the GHG emissions were projected to increase over the next 20 years in BAU. In 2020, the total GHG emission was 14,757 ± 194 $MtCO_2e$, which represented a decline of 43.8 ± 0.8% per GDP unit compared with 2005. The share of non-fossil energy in the TPES was 13.5 ± 0.7%. In 2030, the total GHG emission was 17,959 ± 747 $MtCO_2e$, which represented a decline of 60.2 ± 1.7% per GDP unit compared with 2005. The share of non-fossil energy in the TPES was 19.8 ± 2.5%. The emission peak of 19,409 ± 1124 $MtCO_2e$ was reached in 2044, after which there was a slow decline. Thus, without additional and explicit efforts to mitigate climate change, China is unlikely to achieve the INDC goals, especially the goals of popularizing non-fossil energy and achieving peak emissions as soon as possible.

After the Copenhagen Climate Change Conference in 2009, China published a series of policies to mitigate climate change. According to the Energy Development Strategy Action Plan (2014–2020), the share of coal in the TPES fell below 62%, while the share of natural gas increased to 10%. The amount of installed capacity for nuclear, hydro, wind, and solar generation was 58, 350, 200, and 100 GW, respectively, and the utilization of thermal energy reached 50 million tons coal equivalent by 2020 [15]. The electricity generated from non-hydro renewable energy for power plants reached 9% before 2020 according to the Guiding Opinions on Establishing a Guiding System for Renewable Energy Development and Utilization Targets [28]. By considering these policies, API suggested that China is very likely to outperform the strict INDC goal. The total GHG emission in 2020 was projected to be 13,537 ± 194 $MtCO_2e$, which represented a decline of 48.4 ± 0.8% per GDP unit compared with 2005.

The share of non-fossil energy in the TPES was 16.1 ± 0.7%. The total GHG emission peaked in 2030 with 14,428 ± 747 $MtCO_2e$, which represented a decline of 67.6 ± 1.7% per GDP unit compared with 2005. The share of non-fossil energy in the TPES was 24.7 ± 2.5%. The decrease after the peak was also more significant than in BAU (Figure 2a).

3.2. EU

The GHG emission trend in the EU has declined since 1990, and this was projected to continue in BAU, with an emission of 4430 ± 56 $MtCO_2e$ in 2020 (18.8 ± 1.0% lower than the 1990 level) and 4415 ± 217 $MtCO_2e$ in 2030 (19.1 ± 3.9% lower than the 1990 level), although this does not meet the minimum goal of the EU's INDC, especially for 2030. The EU's policies to mitigate global warming were published in the "2020 climate and energy package" [29] and "2030 climate and energy framework" [30]. The main strategies to be adopted are a 20% improvement in energy efficiency and the generation of 20% of total energy from renewables in 2020, with a further increase to a 27% improvement in energy efficiency in 2030, and at least a 45% share of renewable energy in the electricity sector. As a result, in API there was an accelerated downtrend compared with the past two decades. The emission in 2020 was 4003 ± 56 $MtCO_2e$ (26.6 ± 1.0% lower than the 1990 level), which clearly would exceed the 20% target. The emission in 2030 was 3396 ± 217 $MtCO_2e$ (37.8 ± 3.9% lower than the 1990 level), which is very close to the 40% target (Figure 2b).

3.3. US

The energy consumption per capita in the US was the highest of the four regions investigated and total GHG emissions have been maintained at a high level for several decades. In BAU, the emission trend was projected to rise again after a hiatus in recent years and reached 7000 $MtCO_2e$ after 2040, with the gap to the INDC target growing larger. In 2015, the Obama administration proposed the Clean Power Plan (CPP) [31], which was an ambitious effort to reduce GHG emissions. The CPP aims to reduce emissions from the power generation sector by 32% below 2005 levels by 2030, by increasing the share of low-carbon electricity generation and demand side efficiency, for example, by increasing the share of non-hydro renewables in electricity generation to 20% by 2030 [32]. In API with CPP implemented, the GHG emissions immediately declined and fell below 4000 $MtCO_2e$ after 2060, but in 2020 (6269 ± 49 $MtCO_2e$) and 2025 (6048 ± 124 $MtCO_2e$), they were still 233 $MtCO_2e$ and 373 $MtCO_2e$ above the INDC target. However, the Trump administration has withdrawn the CPP for further review [33], which has resulted in a slowdown of the development of renewables in US. In this case, the GHG reduction would be mainly dependent on energy efficiency improvements, and the projected emissions remained above 6000 $MtCO_2e$ until 2060 (Figure 2c).

3.4. India

India will become the largest developing country in the future. Both the economy and population have increased rapidly, which has resulted in a continuous increase in GHG emissions. In 2020, the total projected GHG emissions in BAU were 4639 ± 162 $MtCO_2e$, which represented a decline of 23.0 ± 2.7% per GDP unit compared with 2005. In 2030, the total GHG emissions were 7355 ± 627 $MtCO_2e$, which represented a decline of 35.1 ± 5.5% per GDP unit compared with 2005. India could therefore achieve its INDC target without any special effort. However, API showed that India could achieve further emission reductions with the help of policies such as the 12th Five-Year Plan [34] and the Jawaharlal Nehru National Solar Mission [35], which has the aim of producing 175 GW of renewable power capacity by 2022 (100 GW solar, 60 GW wind, 10 GW biomass, and 5 GW small-scale hydro). This would increase the share of non-fossil fuel based power generation capacity to 40% of the total installed electric power capacity by 2030. Taking this into consideration, the emissions in 2020 and 2030 were only 3801 ± 162 $MtCO_2e$ and 5286 ± 627 $MtCO_2e$, which represented a decline of 36.9 ± 2.7% and 52.7 ± 5.5% per GDP unit compared with 2005, hugely exceeding the INDC targets (Figure 2d).

3.5. Comparisons and Actions among Different Countries

First, we focused on the ambition of emission reductions, which could be determined by the differences in the projected emissions for BAU and the median values of the INDCs (Table 3). The results showed that the ranking of the emission reductions in terms of their overall ambition was US > EU > China > India, with the first three regions projected to have a reduction of more than 1000 $MtCO_2e$ in 2030 (US in 2025), while India's INDC was even higher than both the 2020 and 2030 targets in BAU. This ranking was in accordance with the common but differentiated responsibilities and respective capacities, when taking historical emission and capability to act into consideration [39]. Second, we considered the execution of pledges, which could be measured by the difference in emissions between the median of the INDCs and API results (Table 3). It was found that the execution ranking was China > India > EU > US, with China and India having more than 2000 $MtCO_2e$ in additional reductions in 2030 exceeding their INDC targets, and the EU just meeting its INDC target, while the US was about 300 $MtCO_2e$ above its INDC target under CPP. Finally, we considered the proportion of clean energy generation in the overall energy production sector and related actions in the future. Figure 3 shows the share of non-fossil energy in TPES. EU has the highest percentage and a boom is coming in the next decade, which requires the reduction policies been carried out efficiently. For example, introducing incentive policies like tax preferences and free parking for electric vehicles to ensure ban on fuel vehicles [24]. As for US, actually, the movement by many states and subnational sectors to reduce GHGs might bring out a decreasing emission trend in long term way. But comparing with EU and China, the clean energy process in US still has a potential to accelerate. China and India experienced a high-speed economic development supported by a large amount of fossil fuels consumption, which was accompanied with a decline of clean energy proportion. This is a universal phenomenon for developing countries, share of fossil in TPES increased 4% between 1990 and 2014 for all non-OECD countries, while it fell 4% for all OECD countries with proven technology in clean energy field [23]. To achieve a global target of reduction, emission from electricity and heat generation is required to drop down immediately [24]. Thus support of clean energy technology from developed countries to developing countries is essential for the latter to get rid of the dependence on fossil and raise their ambition of reduction pledges.

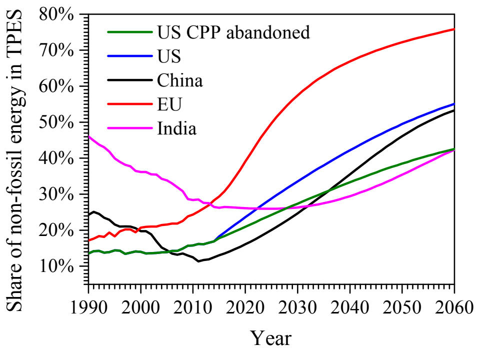

Figure 3. Share of non-fossil energy in TPES for API.

Table 3. Differences in the projected emissions for the two scenarios and the median values of the Intended Nationally Determined Contributions (INDCs) of China, EU, US, and India.

Countries	2020	2025 or 2030	2020	2025 or 2030
	BAU—INDC		INDC—API	
China	−339 $MtCO_2e$	1039 $MtCO_2e$	1560 $MtCO_2e$	2268 $MtCO_2e$
EU	336 $MtCO_2e$	1140 $MtCO_2e$	90 $MtCO_2e$	−122 $MtCO_2e$
US	732 $MtCO_2e$	1382 $MtCO_2e$	−354 $MtCO_2e$	−554 $MtCO_2e$
India	−28 $MtCO_2e$	−25 $MtCO_2e$	867 $MtCO_2e$	2095 $MtCO_2e$

This work improved the statistical method and established a deeply extended model to decompose emission into energy- and economy-related variables, which could be used to quantitatively estimate the policy impacts. However, this study still includes uncorrected problems that could be addressed in future studies. For example, the statistical sectors are not unified and updates are not synchronized among national level and IEA, which results in some uncertainties in the model and needs attention in a "global stocktake".

4. Conclusions

This study investigated the likely variation of GHG emissions from the EU, US, China, and India over the next 50 years, using a newly developed model that was based on a statistical analysis of socioeconomic development and energy production, from which four main conclusions were derived.

(1) In API, with all existing energy policies fully implemented, the EU's emissions fell from 4160 $MtCO_2e$ in 2020 to 2340 $MtCO_2e$ in 2060, while the US's emissions fell from 6330 to 4020 $MtCO_2e$ during the same period. However, if the CPP were to be abandoned, the US's GHG emissions would remain above 6000 $MtCO_2e$/year until 2060. China's emissions peaked in 2030 (14,428 $\pm$ 747 $MtCO_2e$) and then rapidly slowed, while India's emissions grew until 2060 and may reach 10,000 $MtCO_2e$.

(2) The INDCs for the EU and US were remarkably ambitious in terms of emission reductions compared with BAU. The US is aiming for a reduction of more than 700 $MtCO_2e$ in 2020 and 1300 $MtCO_2e$ in 2025, while the EU is aiming for a reduction of more than 300 $MtCO_2e$ in 2020 and 1100 $MtCO_2e$ in 2030. It was found that the EU is probably able to achieve its pledge, while the US will still have a deficit of 370 $MtCO_2e$ in 2025 under the CPP.

(3) In BAU, China's GHG emissions were almost equal to the minimum INDC target in terms of intensity (GHG emission per GDP), but the peak occurred in 2044 (19,409 $\pm$ 1124 $MtCO_2e$), which was 14 years later than the Chinese pledge. India's emissions were already close to the strict INDC emission intensity target. In API, China and India both achieved an extra reduction of about 2000 $MtCO_2e$ exceeding their INDC targets in 2030.

(4) Acceleration of clean energy process is essential to reach a more ambitious global reduction. Developed countries need incentive policies to ensure their target in the next decade and provide developing countries with technology support to help them reverse the increasing trend on fossil consumption.

Acknowledgments: This work was financially supported by the National Key Research and Development Program of China (Grant No. 2016YFA0602704 and 2016YFA0602800), National Natural Science Foundation of China (Grant No. 41771050) and Reform and Development Research Program of Ministry of Science and Technology "Imperative and significant problems to addressing climate change after Paris Conference".

Author Contributions: All of the authors contributed extensively to the work. Y.L. and F.W. conceived and designed the experiments; Y.L. performed the experiments and analyzed the data; J.Z. gave suggestions for modifications to the manuscript; F.W. and Y.L. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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