energies

MDPI

Article

Peaking China's CO_2 Emissions: Trends to 2030 and Mitigation Potential

Qiang Liu [1], Alun Gu [2], Fei Teng [2,*], Ranping Song [3] and Yi Chen [1]

[1] National Center for Climate Change Strategy and International Cooperation, Beijing 100038, China; liuqiang@ncsc.org.cn (Q.L.); chenyi@ncsc.org.cn (Y.C.)
[2] Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China; gal@tsinghua.edu.cn
[3] World Resource Institute, Washington, DC 20002, USA; RSong@wri.org
* Correspondence: tengfei@tsinghua.edu.cn; Tel.: +86-10-6278-4805

Academic Editor: Wei-Hsin Chen
Received: 21 November 2016; Accepted: 18 January 2017; Published: 11 February 2017

Abstract: China has submitted its nationally determined contribution to peak its energy-related emissions around 2030. To understand how China might develop its economy while controlling CO_2 emissions, this study surveys a number of recent modeling scenarios that project the country's economic growth, energy mix, and associated emissions until 2050. Our analysis suggests that China's CO_2 emissions will continue to grow until 2040 or 2050 and will approximately double their 2010 level without additional policy intervention. The alternative scenario, however, suggests that peaking CO_2 emissions around 2030 requires the emission growth rate to be reduced by 2% below the reference level. This step would result in a plateau in China's emissions from 2020 to 2030. This paper also proposed a deep de-carbonization pathway for China that is consistent with China's goal of peaking emissions by around 2030, which can best be achieved through a combination of improvements in energy and carbon intensities. Our analysis also indicated that the potential for energy intensity decline will be limited over time. Thus, the peaking will be largely dependent on the share of non-fossil fuel energy in primary energy consumption.

Keywords: emission peaking; China; mitigation

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC AR5) states that, if the increase in global mean surface temperature is to have a likely chance of being limited to two degrees Celsius by 2100, the global "budget" left for carbon emissions is less than 1778 Gt CO_2 [1]. This space will be exhausted in less than 30 years if global carbon emissions continue their current trend. China is both the largest developing country and the largest CO_2 emitter in the world. Low-carbon development has become an urgent need both domestically and internationally. China's rapidly growing energy consumption and its coal-dominated energy mix create additional and serious environmental problems, including local air pollution and depletion of water resources, as well as the possibility of energy insecurity.

In this context, China has made great strides in controlling fossil-fuel carbon emissions and has increasingly taken on a leadership role in combating global climate change and moving to a cleaner and more efficient low-carbon economy. As Vice Premier Gaoli Zhang pointed out, responding to climate change is necessary if China is to achieve sustainable development at home and fulfill its international obligations as a responsible major country [2]. The 12th Five-Year-Plan (FYP) period (2011–2015) marked a new era in China's climate actions. The country incorporated binding energy- and carbon-intensity reduction targets, and non-fossil energy (nuclear, hydro, solar, wind, biomass, and geothermal) targets into China's top economic and social development plan, marking the institutionalization of domestically enforceable climate-change policies. To achieve these targets, the government has developed and implemented a suite of plans and policy instruments, and is on track to beat its 2015 targets [3]. By 2014, China had reduced its energy intensity and CO_2 emissions intensity by 29.9% and 33.8% respectively, compared to 2005 levels [4].

In 2014, China pledged to peak its CO_2 emissions in around 2030, with the intention of trying to peak earlier, and to increase the proportion of non-fossil fuels in its primary energy consumption to about 20% in 2030 [5]. As input to international climate change negotiations under the United Nations Framework Convention on Climate Change, Intended Nationally Determined Contributions (INDCs) outline the post-2020 climate goals and actions that countries intend to undertake. In 2015, China's INDC echoed the peak year and CO_2 intensity goals, and also put forward two additional goals for 2030: (1) reducing carbon intensity by 60%–65% below 2005 levels; and (2) increasing its forest carbon stock volume by around 4.5 billion cubic meters above 2005 levels [6].

How might these goals be achieved? In order to understand how China might develop its economy while controlling CO_2 emissions, this paper surveys a number of recent modeling scenarios that project the country's economic growth, energy mix, and associated emissions for the coming decades.

In Section 2, this paper first examines several "reference" scenarios. They project that China's emissions will continue to increase and, by the target year of 2030, will have grown by anywhere between 21% and more than 100%. The paper then examines a number of "alternative" scenarios that assume the implementation of additional, more aggressive, policies. Eight out of twelve of these alternative scenarios project that CO_2 emissions will peak or plateau between 2030 and 2040 and decline thereafter, while four scenarios project an emissions peak around 2020. The paper then provides a more detailed comparison of the scenarios, highlighting their results, and examining their underlying assumptions about key driving forces behind China's development and how each of them can impact CO_2 emissions. Section 3 analyzes the interactions among these drivers that will determine how early, or late, the peak in emissions is likely to occur, at what level, and how steeply emissions will decline afterwards. Section 4 provides a more in-depth analysis of one alternative scenario, to illustrate how a CO_2 emissions peak could be achieved in 2030 and how CO_2 emissions could be steeply reduced by 2050. This alternative scenario suggests that such a development path can be achieved through deep de-carbonization of the economy and the use of advanced technologies to enable major efficiency gains, particularly in the industry, transport, and construction sectors. Section 5 presents an uncertainty analysis of the factors that are likely to influence the timing of China's CO_2 emissions peak. Section 6 provides a summary of conclusions based on the scenario analysis and makes recommendations on policy actions that will be important to achieve deep de-carbonization of China's economy.

2. Comparison of Scenarios

This section in this paper surveys energy- and emissions-modeling scenarios for China from 12 recent representative studies (see Table A1 in Appendix A). Most of these studies were published after 2010 and they reflect the most recent projections made by the relevant research teams.

It is difficult to make comparisons across models because of their different methodologies, macro-economic drivers, embedded assumptions, parameters within models, and different storylines assigned by the modelers. Nevertheless, it is still valuable to interpret the impacts of different social and economic assumptions on China's long-term energy transition and shifts in the energy mix. Despite the differences among scenarios, the results still provide reasonable indications of China's possible emissions pathways. The information presented here can provide a useful input for policymakers in China as they confront energy-related decision-making in the coming decades, and for international audiences as they seek to understand the implications of China's climate commitments and policies.

The literature on energy and climate modeling includes three broad categories of scenarios. The first category is the so-called "no new policy scenario", which includes energy or climate policies implemented before a base year or "cut-off year" (for example, 2010); assumes that no new policies will be adopted after the base year; and projects the emission trends under these policies assumptions. The second category is the "current policy scenario", which projects emissions under currently implemented and planned policies. (Planned policies are those policies that have not yet been implemented at the time in the base year but have been included in well-established policy proposals.) The third category is the "alternative scenario", which might not be based on current or planned policies, but instead assumes the adoption of breakthrough technologies, and innovative policy and behavior change. Alternative scenarios are based on technologies, policies, and measures that encourage a shift in the patterns of both energy consumption and carbon emissions away from past trends. Alternative scenarios are based on predetermined storylines, such as strong carbon pricing or adherence to low carbon-development pathways.

In this paper, we combine a number of "no new policy scenarios" with "current policy scenarios" to form the category "reference scenarios". The rationale is that it is difficult to separate the first two categories based on information contained in the literature. The existing literature doesn't clearly demonstrate which policies have been considered in the scenarios and which have not, and the stage of policy implementation is also often unclear. Thus, in this section, we focus our analysis on two categories only: reference scenarios and alternative scenarios. In particular, our definition of reference scenarios cannot be conflated with business-as-usual (BAU) scenarios. Scenarios categorized as "BAU" generally explicitly exclude some current or planned policies, whereas our reference scenarios include some scenarios that include such policies. This is important to consider in any efforts to compare efforts among countries. We summarized the major features of the various models surveyed in this paper. Summary Table A1 and additional information of these models are provided in Appendix A.

2.1. CO_2 Emissions: Reference Scenarios

Figure 1 shows the range of projected CO_2 emissions under the "Reference Scenarios" that were collated for this paper. It should be noted there is also a difference in emission of base year 2010. Such difference is largely due to the choice of different inventory data that different models use for calibration [7]. For year 2030, all reference scenarios project a continuously increasing trend of China's emissions relative to the 2010 level, although the increase factor differs across models. The lowest estimate is from AIM-Enduse (Asian-Pacific Integrated Model Enduse), which projects a 21% increase by 2030; the highest is from GCAM 3.0 (Global Change Assessment Model), which projects a 119% increase in year 2030. Three Chinese models (China-MARKAL, PECE and ERI) project emissions increases that range from 68% to 74% above levels in 2010; this is very close to the median value of 77% among all scenarios surveyed. In terms of absolute emissions in year 2030, the models project a range from 9.6 to 17 Gt CO_2, with a median of 14.6 Gt CO_2.

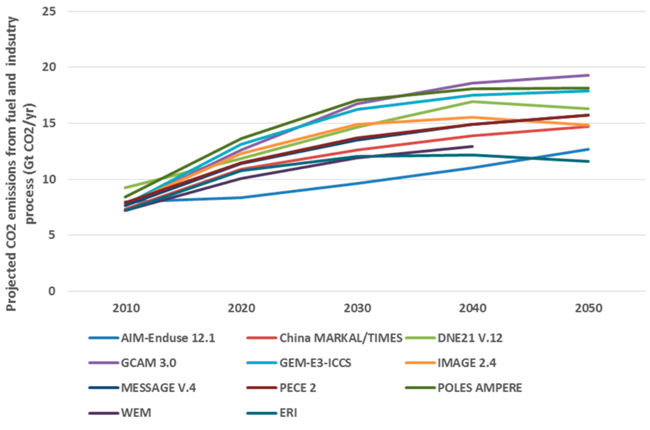


Figure 1. China's CO_2 emissions, 2010–2050, projected by Reference Scenarios. Source: See Table A1 for data sources for each scenario in Appendix A.

For year 2050, the reference scenarios project that emissions will increase by a factor between 59% and 153%, relative to the 2010 level, with a median value of 101%. That is, emissions in year 2050 are forecast to be approximately double the emissions level of 2010. In terms of absolute emissions, the models project a range from 12.7 to 19.3 Gt CO_2 with the median value being 15.7 Gt CO_2.

2.2. CO_2 Emissions: Alternative Scenarios

Many alternative scenarios have been designed and reported, using various energy modeling platform comparison exercises, for example, AMPERE, EMF, AMF, and ROSE. Most of these scenarios have been designed to achieve a given global emissions goal. In these cases, a specific country's emissions path is determined by the global emissions budget and the principle of budget allocation among countries, rather than being determined by countries' policies.

To enable emissions analysis based on policy strength, the current study uses carbon price as a proxy variable to select scenarios with comparable policy strength. In this study, the carbon price proxy is set at USD7–USD10 in 2020 and then roughly doubled every ten years until 2040. The 2020 carbon price proxy is set at this level for two reasons: Firstly, under such an assumption, the sectors that account for about 4% of China's GDP would be heavily affected, producing a comparable effect to that of the EU case under the 20 euro carbon price, indicating strong policy effort. Secondly, China will implement a national emission trafing system (ETS) starting from year 2017 based on seven provincial pilots, the highest carbon price in those pilots are within this range and provide a reasonable assumption for the carbon price in national ETS as an indicator for the stringency of climate policies in China.

Figure 2 shows the range of projected emissions under the "Alternative Scenarios" selected from the literature. For year 2030, the models' projected emissions range from 8.1 (AIM-Enduse) to 13.7 Gt CO_2 (GCAM3.0), with a median of 10.3 Gt CO_2. Compared with emissions in 2010, the models project a median increase of 38%, which is significantly lower than the projected increase under the reference scenarios. Between 2010 and 2050, the models' projected emissions range from a decrease of 40% (AIM-Enduse) to an increase of 44% (GCAM3.0), with a median decrease of 3%. In terms of absolute emissions, the models project a range from 4.7 (AIM-Enduse) to 11 Gt CO_2 (GCAM3.0) with a median of 7.4 Gt CO_2.

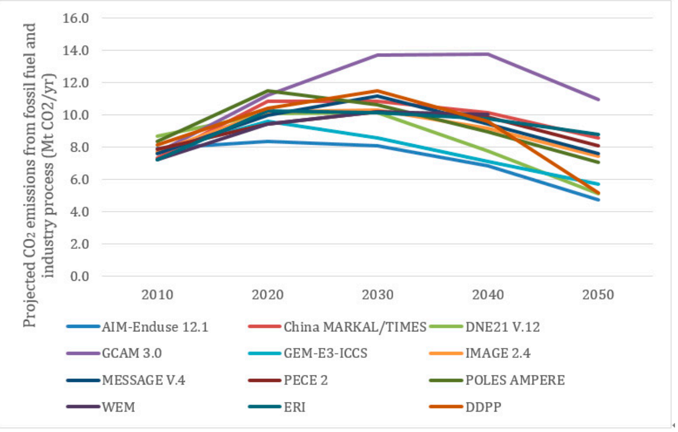


Figure 2. China's CO_2 emissions, 2010–2050, projected by Alternative Scenarios. Source: See Table A1 for data sources for each scenario.

2.3. Peak Years and Levels of CO_2 Emissions

As Figure 1 demonstrated, most models project that emissions under reference scenarios will continue to increase through 2050, though three models project peaking around 2040 (IMAGE, DNE21, and ERI). For models that project a peak in 2040, the peaking levels range from 12.2 Gt CO_2 (ERI) to 17 Gt CO_2 (DNE21), with a median of 15.5 Gt CO_2. The average annual growth rate (AAGR) of emissions across all reference scenarios is 4.4% from 2010 to 2020, 2.1% from 2020 to 2030, 0.6% from 2030 to 2040, and 0.1% from 2040 to 2050.

Figure 2 shows that the majority of the alternative scenarios envisage a CO_2 peak in 2030, while four models (AIM-Enduse, GEM-E3, Poles and ERI) project a peak in 2020 and one model (GCAM3.0) projects a peak as late as 2040. The peaking levels range from 8.4 Gt CO_2 (AIM-Enduse) to 13.7 Gt CO_2 (GCAM), with a median value of 10.3 Gt CO_2. The AAGR of emissions across all alternative scenarios is 2.8% from 2010 to 2020, 0.12% from 2020 to 2030, −0.7% from 2030 to 2040 and −2.4% from 2040 to 2050 (calculated using the median value of all scenarios). The alternative scenarios thus seem to suggest that China's emissions will plateau between 2020 and 2030, at the relatively lower median AAGR of 0.12%, and nine out of twelve scenarios show an AAGR of less than 0.8%.

The exact year in which CO_2 emissions will peak will be heavily influenced by the fluctuation of macroeconomic parameters (notably GDP, see Sections 3.2 and 5). Policy attention, therefore, might more productively focus on the total cumulative emissions that might be expected over the coming decades.

2.4. *Cumulative Levels of CO_2 Emissions*

The recent IPCC AR5 report and other scientific publications have made clear the strong relationship between cumulative CO_2 emissions and global temperature increase. This highlights the importance of examining cumulative CO_2 emissions under a range of scenarios. According to the IPCC AR5, to maintain a likely chance of limiting the mean global temperature increase to 2 °C above preindustrial levels, the "emissions budget" should not exceed 3666 Gt CO_2. As of 2011, the world had already emitted roughly 1888 Gt CO_2 [1]. Thus, a global budget of about 1778 Gt CO_2 remains for all GHG emissions from 2012 onward.

Projections of China's cumulative energy-related CO_2 emissions from 2012 to 2050 differ among the various reference scenarios, ranging from 387 Gt CO_2 for AIM-Enduse to 617 Gt CO_2 for the POLES model, with a median of around 535 Gt CO_2. The cumulative emissions over 2012–2050 across the alternative scenarios range from 286 Gt CO_2 (AIM-Enduce) to 473 Gt CO_2 (GCAM), the median is 371 Gt CO_2 (shown in Figure 3).

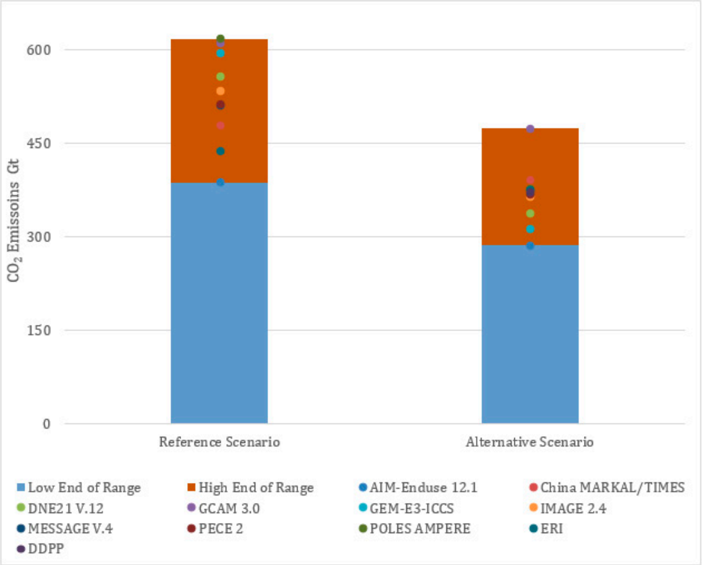


Figure 3. Comparison of cumulative emissions in 2050 under Reference Scenarios and Alternative Scenarios. Note: Cumulative emissions are calculated by linearly interpolating projected emissions levels from scenarios.

3. Understanding Peak Emissions

Scenarios are useful tools for understanding the dynamics of Chinese emissions and preparing for a long-term economic and energy transformation. However, this paper has already demonstrated the wide diversity of projected emissions paths for China, even within the same broad category (such as reference scenarios or alternative scenarios). Before we can gain more valuable insights from these scenarios, it is important to understand why they are so different.

3.1. Key Driving Forces Impacting the Timing of Peak Emissions

In this analysis, we use a decomposition analysis framework to compare emissions scenarios across models and allow us to better understand the driving forces that largely determine cumulative CO_2 emissions and therefore the timing and level of a CO_2 emissions peak. The framework is explained in more detail in following equations.

The methodology we use to analyze various scenarios is mainly based on the Kaya equation [8], which disaggregates CO_2 emissions according to the following driving forces: population (Pop in Equation (1)); per capita GDP (GDP/Pop); primary energy intensity of economic activities (Energy/GDP), which shows energy consumption per unit of GDP in monetary value; and emissions factor of per unit energy consumption (CO_2/Energy).

$$\mathrm{CO_2} = \mathrm{Pop} \times \frac{\mathrm{GDP}}{\mathrm{Pop}} \times \frac{\mathrm{Energy}}{\mathrm{GDP}} \times \frac{\mathrm{CO_2}}{\mathrm{Energy}} \tag{1}$$

The numerical methods we adopt for the decomposition of the Kaya formula are based on so-called LMDI (Logarithmic Mean Divisia Index) methods which allow decomposition without residuals. This method firstly decomposed and allocated the change of carbon emissions to different driving forces as shown in Equation (2):

$$\Delta\mathrm{CO_2} = \Delta\mathrm{CO_2}_{\mathrm{Pop}} + \Delta\mathrm{CO_2}_{\mathrm{GDP/Pop}} + \Delta\mathrm{CO_2}_{\mathrm{Energy/GDP}} + \Delta\mathrm{CO_2}_{\mathrm{CO_2/Energy}} \tag{2}$$

The $\Delta\mathrm{CO_2}_{\mathrm{Pop}}$ and other elements in Equation (2) can be further calculated based on the following equation:

$$\Delta\mathrm{CO_2}_{\mathrm{Pop}} = \frac{\mathrm{CO_2^T} - \mathrm{CO_2^0}}{\mathrm{lnCO_2^T} - \mathrm{lnCO_2^0}} \times \ln\frac{\mathrm{Pop^T}}{\mathrm{Pop^0}} \tag{3}$$

In this paper, the scenarios in various models are decomposed based on ten-year intervals, from 2010 to 2050, which are based on the data we collected from various models.

Furthermore, considering dynamic assumptions and ignoring two orders terms, the interrelationship between these annual rates of change can be abbreviated as [8]:

$$\frac{\mathrm{CO_2^T} - \mathrm{CO_2^0}}{\mathrm{CO_2^0}} = \frac{\mathrm{Pop^T} - \mathrm{Pop^0}}{\mathrm{Pop^0}} + \frac{\mathrm{GDP/Pop^T} - \mathrm{GDP/Pop^0}}{\mathrm{GDP/Pop^0}} - \frac{\mathrm{Energy/GDP^0} - \mathrm{Energy/GDP^T}}{\mathrm{Energy/GDP^T}} - \frac{\mathrm{CO_2/Energy^0} - \mathrm{CO_2/Energy^T}}{\mathrm{CO_2/Energy^T}} \tag{4}$$

$$\beta_c \approx \beta_p + \beta_{pg} - \gamma_{ge} - \gamma_{ec} \tag{5}$$

where β_c is the growth rate of CO_2 emission, β_p is growth rate of population, β_{pg} represents GDP annual growth rate, γ_{ge} represents annual decline rate of primary energy intensity, and γ_{ec} is decline rate of CO_2 intensity of energy use.

As presented in Equations (4), the four major drivers of emissions are population growth, GDP growth, energy consumption, and the average emissions factor of the energy mix. The growth of population and GDP will drive the emissions increase, and the improvements in energy intensity and energy mix will offset the upward trend. The peaking of emission—or the dynamics of change of emissions—can therefore be presented as the relationship among these driving factors:

- The interrelationship between the decline rate of carbon intensity of GDP and GDP growth rate. One necessary condition for CO_2 emissions to peak is that the annual decline rate of CO_2 intensity of GDP should be larger than the annual growth rate of GDP;
- The interrelationship between the decline rate of carbon intensity of energy use and the growth rate of energy consumption. The decline rate of carbon intensity of energy use must be larger than the growth rate of energy consumption;
- The interrelationship between the annual decline rate of per capita CO_2 emissions and the annual growth rate of population. In order to reach a CO_2 emissions peak, the annual decline rate of per capita CO_2 emissions must be greater than the annual growth rate of population.

The relationship between energy consumption, economic activity and carbon emission can be further explored by regression analysis. For example, by using environmental Kuznets curve hypothesis, researchers have analyzed the importance of state-level relationship between emission and income [9], spatial interaction [10] and spatial dependence between states [11,12]. Meta-analysis is another statistical technique to combine the results of several studies that address a set of related research hypotheses [13,14]. However, due to the incompleteness of our dataset, the regression study cannot be implemented. Future work could include expanding our dataset to enable a more insightful regression analysis based on environmental Kuznets curve or meta-analysis.

3.2. Summary of Conclusions from the Decomposition Analysis

3.2.1. Reference Scenarios

Both reference scenarios and alternative scenarios share the same population assumptions. According to the projections, the population AAGR between 2010 and 2020 is in the range of 0.3% to 0.7% (the actual AAGR between 2010 and 2014 was 0.5%) [15]. The reference scenarios' projections of average annual GDP growth between 2010 and 2020 range from 6.2% to 11% (actual AARG between 2010 and 2014 was 8.1%) [15] indicating a much higher level of uncertainty, which is reflected in the wide range of emissions projections in the reference scenarios.

The projected total decline in energy intensity over the period 2010–2020 ranges from −24% to −46%, with a median AAGR of −4.5%. Energy-intensity reduction is the second-largest source of uncertainty in the projection of overall emissions in the reference scenarios. The median annual growth rate in per capita GDP across the reference scenarios is 8.6% per year. The reference scenarios project a near-zero improvement in emissions per unit of energy consumption.

The combined result of these various projections is an indicated a median 4.4% increase in emissions annually between 2010 and 2020. For the period between 2020 and 2030, the median annual growth rate in per capita GDP across various scenarios is 4.4% per year, and energy intensity declines at −2.3% per year, again with to a near-zero improvement in emissions per unit of energy consumption. Combining the projections indicates a median 2.1% increase in emissions annually between 2020 and 2030.

3.2.2. Alternative Scenarios

AAGR of emissions across all the alternative scenarios is 2.8% from 2010 to 2020, and 0.12% from 2020 to 2030. This represents a reduction in the growth rate of emissions, relative to that predicted by the reference scenarios, of 1.6% annually between 2010 and 2020 and two% annually between 2020 and 2030. The source of this additional mitigation is the combination of accelerated energy-intensity improvement (energy/GDP) and reduced carbon intensity of energy use. Before 2020, the major contributor is improved energy intensity, which contributes about one%, while reduced carbon intensity of energy use contributes another 0.5% per year. From 2020 to 2030, however, reduced carbon intensity of energy use dominates, contributing about 1.5% per year while the contribution of energy intensity improvement declines to about 0.5% per year.

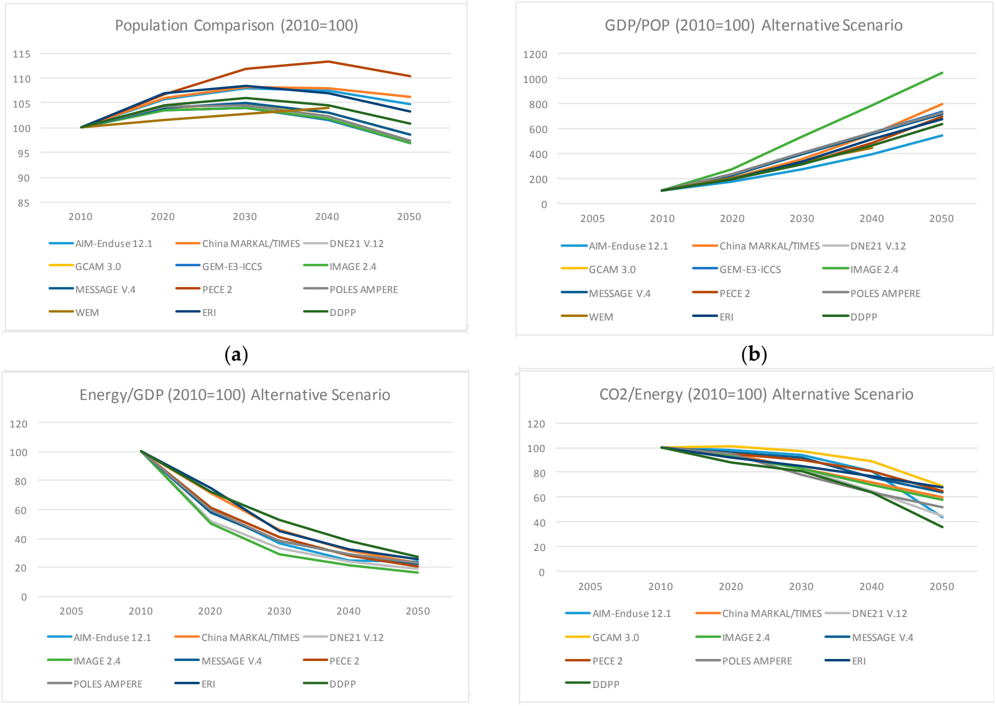
The decomposition analysis reveals two major findings. The first is that the potential for improvements in energy intensity dwindles—in both reference and alternative scenarios—before 2030, which results in the rate of energy-intensity improvement declining to roughly 3% per year around 2030. The second is that, to maintain a higher rate of de-carbonization, the incremental contribution will mainly come from the development of non-fossil-fuel energy sources in the energy mix.

4. The Need for Deep De-Carbonization

As described earlier, the precise year of a peak in China's CO_2 emissions is of less importance than the total cumulative emissions over the coming two to three decades. According to the median projection of the reference scenarios, if more aggressive action is not undertaken, China's emissions between 2012 and 2050 will account for about 30% of the remaining global carbon budget. To avoid this outcome, it is necessary to target a steep decline after the emissions peak has been achieved. This can be realized only through deep de-carbonization of the economy.

4.1. Key Indicators Relevant to Deep Decarbonization

Figure 4 presents comparisons of projections for the time period 2010 to 2050, as developed in the alternative scenarios. They cover the key indicators of population growth, per capita GDP growth, decrease in energy intensity (energy/unit GDP), and decrease in carbon intensity (carbon/unit energy). Most of the alternative scenarios incorporate accelerated de-carbonization into their narratives. However, given the diversity of parameters and assumptions among these scenarios, it is helpful to select and examine one scenario in greater detail. This study has chosen to examine the Deep De-carbonization Pathways Project (DDPP) scenario, in part because the authors were involved in developing the scenario and have access to its underlying assumptions and data that are not universally available for the other alternative scenarios. The aim is to shed light on the conditions (for example, population and GDP growth rates) and the specific social and economic changes that will likely be necessary to underpin the transition to a very low carbon-emissions path that is consistent, not only with China's domestic policy goals, but with achieving the global 2 °C target.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. Comparisons of projections between 2010 and 2050 under Alternative Scenario for four key indicators. (**a**) Population growth; (**b**) per capita GDP growth; (**c**) decrease in energy intensity; and (**d**) decrease in carbon intensity.

4.2. The Deep Decaronization Pathways Project Scenario

The National Center for Climate Change Strategy and International Cooperation Center (NCSC) and Tsinghua University of China have developed the China scenario for DDPP in an attempt to analyze a development path that could bring about an early peak and subsequent steep decline in CO_2 emissions. The DDPP scenario studies China's future energy development and carbon emissions pathway at 10-year intervals extending from 2010 through 2050. The energy consumption and carbon emissions of end-use sectors, including industry, transportation and the building sector are analyzed, whose demands are exogenous and determined by both scenario survey and expert opinion. Power consumption and related carbon emissions are calculated by optimizing the technology options for power generation under a cost-minimization condition. The system cost includes capital costs, fixed and variable annual operation and maintenance costs, costs incurred for import and resource extraction and production, revenues from export, delivery cost, taxes and subsidies.

Summary of Trends Projected in the DDPP Scenario

This section summarizes the key trend developments that might be expected under the assumptions of the DDPP scenario. They should be understood as forecasts, not as statements of fact.

- GDP: China's economy will continue to grow rapidly but, as the economy enters a more mature phase, GDP is predicted to grow at a slower rate in DDPP than in the other reviewed scenarios. By 2050, the projected GDP will be 641% higher than in 2010. Per capita GDP will increase more than six fold between 2010 and 2050;
- Energy consumption and energy intensity: China's primary energy consumption will increase by 75%, from 2482 Mtoe in 2010 to 4351 Mtoe in 2050, reaching a peak of 4598 Mtoe around 2040. Electricity consumption will triple to 11,772 TWh in 2050, and per capita electricity consumption will increase to about 8700 kWh [16] (the average level for developed countries in 2010). (The developed countries refer to United States, Germany, France, and Japan)
- Between 2010 and 2030, energy intensity (energy/GDP) will decline around 50%. Energy intensity will be reduced by 73% in 2050 compared with 2010, through a wide range of actions in different sectors of the economy, primarily the power, transport, building, and industry sectors.

DDPP assumes that China is currently at a more advanced stage of industrialization than of urbanization. Therefore, the industry sector is projected to have a different energy consumption trajectory from that of the building and transport sectors. Industrial energy use is projected to increase by 37% between 2010 and 2050, and the associated emissions are expected to peak at around 7200 Mt between 2020 and 2025. However, energy use in the transport sector is projected to increase by 130% between 2010 and 2050, with associated emissions expected to peak at around 1780 Mt in 2030. Building sector energy consumption is projected to increase by 91% between 2010 and 2050, with emissions expected to peak at around 2650 Mt in 2035. The combined emissions of the transportation and building sectors are projected to decline to 2456 Mt in 2050.

- Carbon intensity of Energy: Shifts in China's energy mix play a key role (see Figure 5). The share of coal in primary energy consumption will fall from 71% in 2010 to 27% in 2050, while the share of non-fossil fuels will increase from 7.9% to 42%. Natural gas will increase its share from 3.8% to 17% over the same period. In 2050, the share of all renewables in total power generation will rise to 52%, while nuclear energy will account for another 20%. The combination of increasing non-fossil electricity and application of carbon capture, utilization and storage (CCUS, see Figure 5) in thermal power generation will reduce the CO_2 emissions per unit of electricity generation in 2050 to less than 10% of the level in 2010.

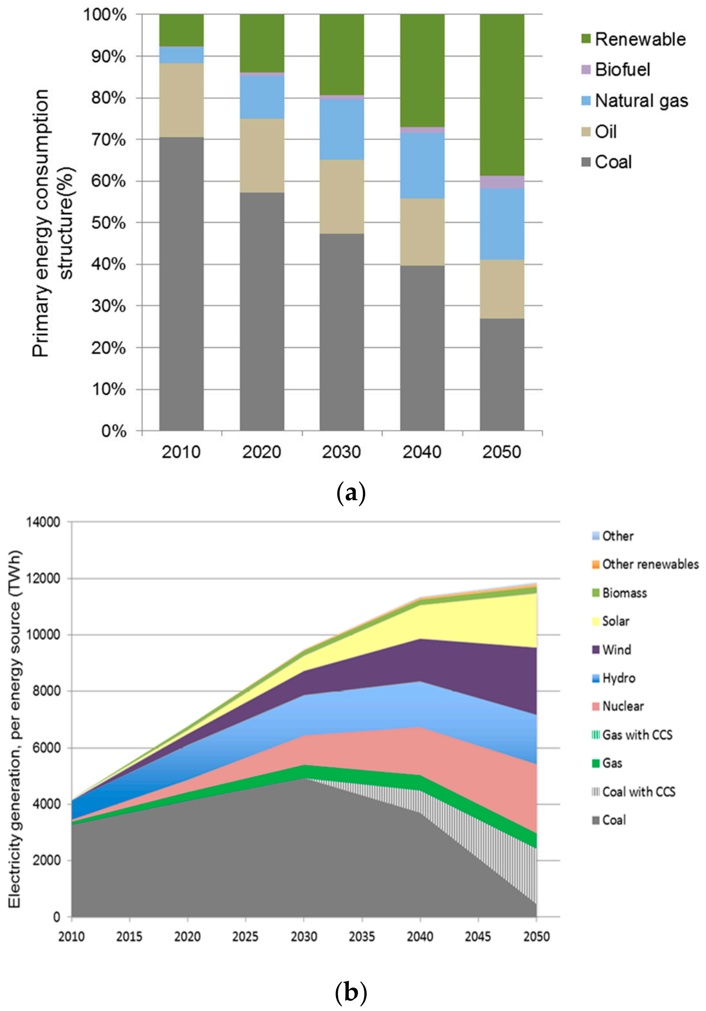
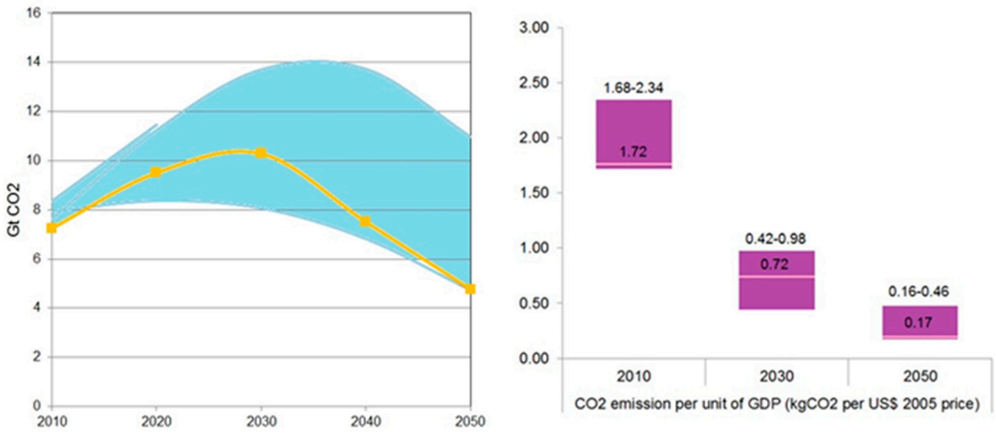


Figure 5. (**a**) Primary energy consumption structure, 2010–2050; and (**b**) electricity production by energy type, 2010–2050. CCS: carbon capture and storage.

With accelerated deployment of CCUS, 2737 Mt CO_2 will be captured in 2050, equal to 32% of the carbon emissions projected by the scenario in the absence of CCUS. This amount is close to the upper limit of what can be expected from China's CCUS development [17].

- CO_2 emissions: In terms of emissions, the result of interactions among the trends described above is as follows:
    - ✓ Energy-related CO_2 emissions are projected to reach a peak around 2030 at 11,477 Mt CO_2 but will decrease significantly to 5173 Mt CO_2 in 2050;
    - ✓ The decline rate of carbon emissions per unit of GDP is projected to increase from 57% in 2030 to 90% in 2050, relative to the 2005 level, demonstrating an acceleration of de-carbonization after 2030 (see Figure 6). This de-carbonization path is consistent with the possible range of scenarios in the IPCC AR5 scenario database [18] that have a greater than 50% probability of achieving the 2 °C goal;
    - ✓ Per capita carbon emissions show a similar trend to total emissions, reaching 7.4, 8.1, 6.8 and 3.8 tons in 2020, 2030, 2040 and 2050, respectively. Per capita carbon emissions peak in 2030, at about the same level as EU per capita emissions in 1990.



(**a**) (**b**)

Figure 6. (**a**) Comparison of DDPP and other scenarios: projected CO_2 emissions; and (**b**) carbon intensity of GDP. Notes: The shaded areas represent the range of CO_2 emissions projections in various alternative scenarios reviewed in Section 2. The orange line represents CO_2 emissions projected by the DDPP scenario (**a**). The pink line represents CO_2 emissions per unit of GDP in the DDPP scenario (**b**). The variation of 2010 data is explained by the fact that some of the alternative scenarios used predicted rather than historical data.

5. Early Peaking or Late Peaking: An Uncertainty Analysis

A number of uncertainties influence China's efforts to peak CO_2 emissions by 2030.

5.1. Population Growth

Of the various factors influencing CO_2 emissions in the Kaya Identity, population growth is the least uncertain. By 2030, China's population is expected to have stabilized and be trending toward zero or even negative growth [19], easing the associated energy service demand. Population growth—at least in the case of China—is therefore a driver that is compatible with earlier peaking of CO_2 emissions.

Other factors such as GDP growth, energy intensity of GDP, and the carbon intensity of energy use are subject to greater uncertainty and need to be analyzed carefully and clearly.

5.2. GDP Growth

As a successful and rapidly industrializing economy, China has experienced remarkably high GDP growth rates. Between 1990 and 2010, China's GDP grew at an average rate of 10.5% per year; it has currently slowed to approximately 7.4% per year [20]. China has paid a price in terms of severe pollution and depleted natural resources but the country might expect both GDP growth rates and environmental damages to stabilize as the economy matures. Nevertheless, the current development pattern which relies primarily on heavy industry is not sustainable for China's future development. Transformation to an innovative, low-carbon development pattern is needed, in which more attention is paid to the quality, as well as the quantity, of economic growth.

Relatively small changes in GDP growth rates can have enormous implications for energy consumption and CO_2 emissions. If the annual average GDP growth rate can be held to 7.5% from 2010 to 2020, then, by 2020, total energy consumption is projected to be 4.8 Gtce, in which case CO_2 emissions would exceed 10 Gtons. However, if the annual average GDP growth rate rises by just 1% and the energy intensity of GDP declines by the same amount, the energy consumption in 2020 would likely increase by 430 Mtce and CO_2 emissions by 750 Mtons.

The DDPP scenario assumes that China's GDP in 2030 is 3.3 times larger than in 2010. However, if China's GDP is four times larger, and the decline rate of energy intensity of GDP remains unchanged, the energy consumption of 2030 would reach 6.65 Gtce. Assuming current trends in non-fossil fuel use remain unchanged, CO_2 emissions would reach 12.5 Gtons, and coal consumption would increase by 600 Mtons in 2030, bringing more substantial environmental issues.

If the annual average GDP growth rate is higher than 5% in 2030, then peaking CO_2 emission by that date would require significant extra effort beyond that assumed in the current DDPP scenario. Based on the experience of developed countries, GDP growth in the post-industrialization period is not likely to exceed 3% annually. Therefore, in the longer term, China's GDP growth is likely to fall back to somewhere in this range after 2030, which ultimately would help accelerate a long-term decrease in CO_2 emissions. Based on China's INDC targets, the country's per capita CO_2 emissions could peak at a substantially lower level—and at a substantially lower per capita GDP level—than those typical of developed countries [18].

It remains the case that China's record of strong economic growth is a factor that increases the odds of a later peaking in CO_2 emissions. However, the greater the rate of decline in energy intensity and carbon intensity, the more scope China will have for economic growth while still meeting its emissions targets. The relationship between GDP growth, energy consumption and associated emissions is not fixed; if China can achieve a dramatic decoupling of these elements, future GDP growth need not create a significant increase in future emissions.

5.3. Decline of Energy Intensity of GDP

China's energy intensity of GDP decreased by 57% between 1990 and 2012 but it remains high—twice the world average, 2.5 times that of the United States and 4.3 times that of Japan in 2010. The primary reason is not that China lags behind in energy efficiency and advanced technologies. China has endeavored to develop energy-saving technologies and energy-efficiency levels are close to developed countries [21]. Rather, China's high energy intensity is mainly due to differences in national economic structure and the product value chain. Industry accounts for more than 40% of total GDP in China. End-use energy consumption accounts for 70% of total energy consumption, of which 50% is consumed by the energy-intensive raw-materials industry [22].

In developed countries, the industrial sector accounts, on average, for less than 30% of GDP. High-tech industries and the service sector account for a large proportion and the energy consumption per unit of added value is quite low. By contrast, China's industrial products are middle to low end in the international value chain, with high energy consumption and low added value.

Because structural factors are primary contributors to China's high energy intensity of GDP, great potential remains for China to decrease it. In the future, energy savings resulting from structural changes in the industry sector and continued technology upgrades will generate major effects, even as the potential for achieving savings through greater efficiency within economic sectors diminishes with the transition away from China's current reliance on heavy industry. The DDPP projects that, from 2010 to 2030, the decline in energy intensity can likely be maintained at an annual rate of 3.0%–3.5%. Thus, the current "immaturity" of China's industry sector is a positive factor that is conducive to an earlier date for peaking CO_2 emissions. After 2030, however, as industrial restructuring and technology upgrades mature, great efforts will be needed to keep the decline rate of energy intensity of GDP at a level of 3%. Significant absolute emissions reductions will depend more on adjustments in the energy mix.

Based on the experience of post-industrial countries, the annual decline rate in the energy intensity of GDP usually does not exceed 2%, while the GDP growth rate usually does not exceed 3%. Slower GDP growth and the adjustment of the energy mix in developed countries could result in CO_2 emissions peaks being achieved and emissions could continue to fall in the post-industrialization period. Therefore, the period 2010 to 2030 represents a window during which China can take advantage of its industrial restructuring and maximize its chances of achieving an early emissions peak. If, on the other hand, China's decline rate of energy intensity of GDP decreases from 3.25% annually (as assumed in the DDPP scenario) to 2.25% annually, then energy demand by 2030 will reach almost seven Gtce, which is 1.34 Gtce more than projected in the DDPP scenario. The corresponding CO_2 emissions would exceed 13 Gtons and achieving the CO_2 emissions peak would be postponed to 2035 or later. Therefore, maintaining a high decline rate in the energy intensity of GDP is a necessary condition to reach an early carbon emissions peak.

5.4. Decline of CO_2 Intensity of Energy Use

CO_2 intensity of energy use can be greatly diminished by the development of energy sources such as hydropower, wind power, solar power, and nuclear power. It also can be diminished by the substitution of natural gas for coal. Non-fossil fuels and natural gas have seen rapid development in recent years but they still account for only a small fraction of total energy supply and fossil-fuel consumption continues to rise to meet growing demand.

Current trends in non-fossil fuels, natural gas, and nuclear energy development, and the projected growth in energy demand of 1.5% per year, are compatible with reaching a CO_2 emission peak by about 2030. By 2030, non-fossil fuels are projected to account for 20%–25% of the energy mix, equivalent to 1.2–1.5 Gtce. The installed capacity of hydropower should reach 400 GW and the installed capacity of wind power and solar power is expected to reach 440 and 350 GW, respectively. The installed capacity of nuclear power is also planned to rise to 150 GW. The annual growth rate of non-fossil fuels keeps 6%–8%. As a result, the CO_2 intensity of energy use should decrease by 20% relative to 2010.

By 2030, new non-fossil energy is projected to be supplied mainly by solar power, wind power, biomass and nuclear energy; usable hydropower resources should be almost fully exploited. Solar energy and wind power have great further potential but energy transportation, storage, grid stability and distribution capacity are all barriers that impede their utilization. Nuclear energy also has great potential but it is subject to perhaps the greatest level of uncertainty among all energy technologies. China currently has 20 GW installed capacity of nuclear power [23]. Following the Fukushima nuclear accident in Japan, China's nuclear energy security was strengthened. Higher standards have been established for the construction of nuclear power plants and the rate of development has slowed. By 2020, operating nuclear capacity is planned to rise to 60 GW, and ccontinue rising to 150 GW by 2030. By that date, more than 10 power stations with installed capacity of 1 GW would be in production every year. The newly increased installed capacity would be more than 10 GW annually, which would meet 20%–30% of energy demand. By 2050, the total installed capacity of nuclear power would approach 330 GW.

However, the path and scale of nuclear power development largely depend on consensus between the people and governments of all levels. If consensus cannot be reached, and nuclear energy development is blocked, greater effort will be needed to develop renewables to meet both increasing energy demand and the non-fossil-fuel target established by China. The future supply of natural gas and oil might be constrained by resource limits and issues of import security. In the absence of serious efforts, a major portion of the energy demand gap is likely to be filled by coal. By 2030, if the installed capacity of nuclear power stations is 50 GW lower than assumed in the DDPP scenario, coal consumption could increase by more than 150 Mtons, creating about 300 Mtons of CO_2 emissions. After 2030, without substantial growth of installed capacity of nuclear energy, the adjustment of China's energy mix would slow down and fossil-fuel consumption would keep rising. The CO_2 emissions peak could be delayed for 5–10 years.

5.5. International Energy Market and Key Technologies

China is increasingly dependent on the international market for its oil and natural gas. Dependence on oil imports reached 58% in 2012, while imports of natural gas accounted for 29% of total natural gas supply. Several forecasts indicate that oil import dependency could rise to 70% and natural gas imports could account for 50% of supply by 2020 and that rising trends could continue to 2030. Import dependency not only challenges national energy security, it also creates great uncertainty regarding the future energy mix. If the international market for oil and/or natural gas should tighten or destabilize significantly, China would probably be forced to consume more domestic coal resources and use more coal chemical technologies. Thus, coal consumption and corresponding CO_2 emissions would be significantly increased. Though China has great potential resources in unconventional gas development, including shale gas and coal-bed methane, uncertainties remain over technology costs and environmental impacts. The state of the future international energy market therefore represents a major negative uncertainty for the trend and timeframe of CO_2 emissions reduction.

CCUS is a key technology with great potential to reduce CO_2 emissions even while China continues to exploit coal resources. Under the DDPP scenario, CCUS is assumed to reduce total CO_2 emissions by one third in 2050. However, CCUS technology still faces many challenges, including unclear national strategies and policies, lack of financing, concern about the integrity of storage, and uncertainty regarding technology innovation. At present, the energy consumption involved in carbon capture is generally considered too high (extra consumption equivalent to 20%–30% of the fuel) and capture costs are significant (about USD15–75 per ton of CO_2 in the power sector, and USD25–55 per ton in the industrial sector) [24]. Without rapid technology innovation, and in the absence of reasonable carbon-pricing mechanisms, large-scale CCUS development faces enormous difficulties and seems likely to have a negative impact relative to the emissions pathway proposed under the DDPP scenario.

6. Conclusions and Policy Recommendations

6.1. Conclusions

China's development needs are to advance people's living standards and eliminate poverty. These needs drive China's economic growth, and the huge production and service demands that push up China's energy consumption and CO_2 emissions. It follows that holding the increase in service demands to a manageable level and transforming industrial production to more sustainable patterns are prerequisites for China's low-carbon development. Policies and measures of the kind assumed in the DDPP scenario, which guide both producers and consumers in different end-use sectors, will be of critical importance in the coming decades.

In this paper, we reviewed recent modeling exercises in order to analyze the impacts of China's climate actions on emissions. Our analysis suggests that, without additional policy intervention, China's CO_2 emissions will continue grow until 2040 or 2050 and will approximately double from their 2010 level. The alternative scenarios, however, suggest that peaking CO_2 emissions around 2030 requires the rate of growth in emissions to be reduced by 2% below the reference level. This would result in a plateau in China's emissions from 2020 to 2030. Expressed in terms of energy intensity, the DDPP scenario suggests that a reduction in energy intensity of 73% compared to 2010 levels will be crucial by 2050.

We have shown that the different models vary greatly in their projections of overall CO_2 emissions. The variation is due mainly to their different assumptions regarding drivers, and the most important difference lies in projections of GDP growth. This fact seems likely to explain why the target in China's INDC is expressed in the form of emissions per unit of GDP (emissions intensity) rather than in the form of an absolute emissions target. This result also suggests that debate over the precise timing of a peak in China's emissions should not dominate the country's approach to policy development. The exact year in which peaking occurs will be overwhelmingly impacted by fluctuations in GDP growth over the next two decades and fluctuations in GDP are subject to significant uncertainty. Nevertheless, it is clear what needs to be done. To peak CO_2 emissions in some year approximately around 2030—and to set China on track to limit cumulative emissions through 2050—China will need additional policies and measures to achieve deeper reductions in its energy intensity per unit of GDP. We also conclude that such reductions need not interfere with China's projected levels of economic development.

As discussed earlier in this paper, the first necessary condition to reach a CO_2 emissions peak is that the annual decline rate of CO_2 intensity of GDP must be higher than the annual growth rate of GDP.

The authors project that China's annual decline rate of CO_2 intensity of GDP between 2020 and 2030 will be between 3.1% and 5.3%, with a higher degree of probability for a decline rate between 3.1% and 4.5%. The World Bank and China's State Council Development Research Center project that China's potential annual GDP growth, assuming proper reform and no major shocks, will be 5% between 2025 and 2030 [25]. These two sets of projections imply, therefore, that if sufficient effort is made to maintain the maximum decline rate in energy intensity—5.3%—China's emissions can peak around the year 2030 while its economy can still grow at its full potential growth rate.

There is further synergy, because the greatest scope for reductions in emissions per unit of GDP lies in the evolution of China's economic structure, principally its shift from heavy industry to a more diverse, service-oriented, and higher value profile, which is one of the chief measures needed for China to achieve its economic potential [25]. Additional efforts to reduce energy intensity will facilitate the transformation of China's development pathway.

The goal of peaking emissions by around 2030 can best be achieved through a combination of improvement in energy intensity (energy per unit of GDP) and in carbon intensity (emissions per unit of energy consumption). The policy debate should therefore focus on measures that will enable reductions of energy intensity and carbon intensity, and how these measures will contribute to reducing the emissions growth rate by 2% below the rate currently projected. This is the essential policy goal that must be pursued if China's emissions are to plateau between 2020 and 2030, and to achieve a steep decline as early as possible.

Our analysis has also suggested that the potential for decline in energy intensity will be limited over time, as industrial transformation is achieved and lower cost efficiency improvements are exploited. Thus the achievement of emissions peaking around 2030 will also be largely dependent on how quickly China can achieve its stated goal regarding the share of non-fossil fuel energy in primary energy consumption.

6.2. Recommendations

Early and effective actions must be launched for each major sector of China's economy.

In the power-generation sector, the government should prioritize the development of non-fossil fuels until they dominate the energy mix of the sector. Electrifying end-use sectors that currently rely on fossil fuels—and generating power from renewable energy sources—are essential steps to achieving deep de-carbonization. The electricity-pricing mechanism should be reformed to enable sustainable development of power sector. Outdated power plants should be phased out as part of an effort to increase the generating efficiency of thermal power plants. Because China's energy system is dominated by coal, scale-up of CCUS technologies in thermal power plants will also be essential.

In the industry sector, the government needs to control major energy-intensive industrial outputs, discourage outdated production capacity, and cultivate strategic emerging industries to enable transformation of the structure of the industry sector. Policies to improve industrial energy efficiency should be continued, including investment in research and development of advanced technologies, and promoting the application of energy-saving techniques and technologies. Coal use in industry needs to be reduced and CCUS application will be needed in energy-intensive industries such as cement, iron and steel, chemicals, and petrochemicals.

In the building sector, the government needs to optimize urban planning and place restrictions on mass demolition of old buildings. While meeting people's needs for improved living standards, the growth in floor area of residential dwellings should be contained at a reasonable level. The government should also improve the energy efficiency of heating supply and electrical appliances and reduce fossil-fuel use by popularizing the use of waste heat and distributed renewables. Additional research and development investment for alternative energy technologies is greatly needed.

In the transport sector, the government needs to slow the growth rate of private transportation service demands through encouraging the use of public transportation and enhancing the implementation of transit-oriented development in urban-construction planning. The government should also require further improvements in the energy efficiency of vehicles and optimize the energy structure of the transport sector by promoting the electrification of trains and cars and accelerating the development of biofuels.

China should promote the transition to a low-carbon energy system by shifting its focus from targeting carbon-intensity control to targeting total carbon-emissions control. China has a carbon-intensity control system in place and has set carbon intensity-reduction targets for each five-year plan; the target for each year is therefore determined. The carbon-intensity reduction target and the energy-intensity reduction target have, together, become the main high-level policy in the 12th FYP for controlling the growth of energy use and CO_2 emissions. This approach is expected to continue during 13th FYP.

China's GDP is likely to grow relatively quickly over the next ten to fifteen years. The policy of reducing energy and carbon intensity will help to control the rate of increase in carbon emissions, but it will not be sufficient to stabilize—much less reduce—total carbon emissions. In the short and medium term, the main task is to slow down the rapid growth of carbon emissions before 2020; this would build a strong foundation for achieving an emissions peak around 2030. A vitally important step is therefore to shift away from carbon-intensity control toward a policy of dual control of carbon intensity and total carbon emissions. To this end, it will be essential to establish the carbon-emission allowance-allocation management system to determine and allocate the carbon-emission allowance for each province, autonomous region, and municipality. In addition, given the overall scale of China's economy and the diversity and complexity of the country's many regions and sectors, it will be necessary to begin with more stringent requirements on the principal sources of carbon emissions, that is, the most carbon-intensive sectors and products. Mandatory carbon-emissions standards could be used as a forcing mechanism to promote the low-carbon transition in key industries and sectors, and the development and use of low-carbon products.

In the long term, it will be necessary to achieve a steady decrease in carbon emissions. This will require the establishment of an economy-wide, total-carbon-emissions-control regulatory system and correspondingly strong mechanisms for implementation and enforcement.

Acknowledgments: The authors gratefully acknowledge the financial support of the National Key Research and Development Program of China (No. 2016YFA0602702) and the National Natural Science Foundation of China (No. 71673162 and No. 71573145).

Author Contributions: Qiang Liu and Fei Teng conceived and designed this article; Alun Gu and Yi Chen collected and analyzed the data; Ranping Song contribute analysis tools; and Qiang Liu, Alun Gu and Fei Teng wrote this paper.

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

Abbreviation

Mt	Million tonnes
Gt	Giga tonnes
Mtoe	Million tonnes of oil equivalent
Gtce	Giga tonnes of coal quivalent
TWh	Terawatt-hour
kWh	Kilowatt-hour
GW	Gigawatt

Appendix A

AIM/Enduse is a bottom-up, technology-rich model based on a linear optimization framework to minimize the system cost, comprising initial fixed costs, operating costs, energy costs, taxes and subsidies.

The user of AIM-Enduse can also choose various constraints to bind the model. The AIM-Enduse world version divides the world into 32 regions and China is represented as a single region.

China-MARKAL is a national energy model with rich bottom-up technology details. It uses MARKAL as the modeling framework, with the objective function of minimizing the total annual cost, which includes annualized investments, annual operating costs, minus revenue from exported energy carriers, plus taxes on emissions and costs of demand losses.

DNE21 is an integrated assessment model consisting of an energy-system model, a macro-economic model, and a climate-change model. Those three models are hard linked. The macro-economic model is driven by exogenous population growth and GDP growth, and generates final energy demand which will be sent to energy system models. The energy-system model will take the final energy demand and minimize the total cost of the energy system. The energy-supply technologies are modeled by a bottom-up approach while the energy end-use technologies are modeled in a top-down approach. The DNE21 model divides the world into 10 regions. China and other neighboring countries are combined into one region.

ERI-3E is a hybrid model that connects a CGE model with a technology-rich, end use sector model. The CGE is used to project the economic development pattern including structures of consumption, investment, and import/export. These projections, in monetary value, are translated into physical terms through the STOCK model to drive the Enduse model. The Enduse model will meet final demand by optimizing the energy system within given constraints.

GCAM is a dynamic-recursive model with technology-rich representations of the economy, energy, and land use, linked to a climate model. GCAM can be used to explore climate-change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. GCAM has been used to explore the potential role of emerging energy-supply technologies and the greenhouse-gas consequences of specific policy measures or energy-technology adoption including; CO_2 capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy-use technology in buildings, industry, and the transportation sectors.

GEM-E3 is a recursive, dynamic, computable, general equilibrium model that covers the interactions between the economy, the energy system, and the environment. The GEM-E3 model simultaneously computes the equilibrium in the goods and services markets, as well as in production factors (labor and capital). The economic agents optimize their objective functions (welfare for households and cost for firms) and determine separately the supply or demand of labor, capital, energy, and other goods. Market prices guarantee a global equilibrium endogenously. Economic production is modeled with a nested CES production function, using capital, labor, energy and intermediate goods. The consumers decide endogenously on their demand for goods and services using a nested extended Stone Geary utility function. The world version of GEM-E3 is based on GTAP 8 and regional aggregation is flexible.

The IMAGE is a dynamic, integrated assessment framework to analyze global change. IMAGE comprises two main systems. The Human or socio-economic system describes the long-term development of human activities relevant for sustainable development. The Earth system describes changes in the natural environment. The two systems are linked by the impacts of human activities on the Earth system, and by the impacts of environmental change in the Earth system on the Human system. The IMAGE framework uses the detailed energy system model "The IMage Energy Regional model" (TIMER) to describe the long-term dynamics of the energy system. TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states.

MESSAGE is a dynamic, linear programming model designed for the optimization of energy supply and utilization. MESSAGE I1 was developed at IIASA based on MESSAGE, a Model for Energy Supply Strategy Alternatives and their General Environmental Impact. The main changes include user-friendly interface for data input and output, all program calls necessary. The data frame have beed desigend to a databank based on keywords, which is easier for data processing aotomaticly. In the mathematical formulation, some options have been eliminated from the model, and the multi-objective option has been developed further. The reference point optimization method, adapted to dynamic modeling into a reference trajectory optimization method, is implemented.

PECE model comprises three sub-models, which include PECE-SE (social economic model); PECE-ESD (energy service demand model) and PECE-ES (energy technology model). PECE-ES model is a bottom-up, non-linear technology optimization model in which least-cost technology choices are made under a series of restrictions (for example, the demand for energy services, the restriction on energy supply, the restriction on technological feasibility, etc.). The costs calculated in the model include annualized fixed cost of recruited devices during that year, variable operation cost (operation and maintenance cost of devices, and fuel cost), cost of installing removal devices (CCUS for pulverized coal-fired power plants, etc.) and cost of emissions taxes (carbon tax, energy tax, etc.). This model is based on the partial equilibrium framework and is used as a tool to estimate future energy demand and emissions. It simulates the flows of energy and materials in an economy, from the source or supply of primary energy and materials, through conversion into secondary energy and materials, to the delivery of various forms of energy to the end-use services. In the model, these flows of energy and materials are characterized through detailed representation of technologies providing an end-use, scenario-driven analysis. The model also considers the existing device quantities in the starting year of the scenario horizon and calculates the retirement of the devices at the end of their life span.

The POLES model is a world simulation model for the energy sector and industrial GHG-emitting activities. It works in a year-by-year recursive simulation (up to 2100) and partial equilibrium framework, simulates international energy prices endogeously and adjusts supply and demand of world regions lag behind. The POLES model combines a high degree of detail on the key components of the energy system and a strong economic consistency, because all changes in these key components are at least partly determined by relative price changes at sectoral level, regarding both demand and supply. Thus, each mitigation scenario can be described as the set of consistent transformations of the initial baseline case that are induced by the introduction of a carbon constraint or carbon value/penalty. The model identifies 43 consuming regions of the world, with 22 energy-demand sectors and about 40 energy technologies; the description of climate-policy-induced changes can therefore be quite extensive. The POLES model relies on a framework of permanent inter-technology competition, with dynamically changing attributes for each technology, for which the model provides dynamic cumulative processes through the incorporation of Two Factor Learning Curves, while price-induced mechanisms of technology diffusion and transformation of the energy demand are also included in the simulations.

WEM is a simulation model covering energy supply, energy transformation and energy demand. The majority of the end-use sectors use stock models to characterize the energy infrastructure. In addition, energy-related CO_2 emissions and investments related to energy developments are specified. Although the general model is built up as a simulation model, specific costs play an important role in determining the share of technologies in satisfying an energy-service demand. In different parts of the model, Logit and Weibull functions are used to determine the share of technologies based upon their specific costs. This includes investment costs, operating and maintenance costs, fuel costs and, in some cases, costs for emitting CO_2.

DDPP model, a bottom-up model, studies China's future energy development and carbon-emissions pathway at 10-year intervals extending from 2010 through 2050. DDPP model is based on four sectors, including the industry, transportation, building, and power sectors, with the prediction function of energy consumption and carbon emissions at national level. DDPP model is driven by service demand and the macro-economy, which are exogenous and determined by both scenario survey and expert opinion. Power consumption and related carbon emissions are calculated using the TIMES model to optimize the technology options for power generation under a cost-minimization condition.

Table A1. Major features of models surveyed in this study.

Model	**AIM-Enduse** [26]	**China-MARKAL** [27]	**DNE-21** [28]	**DDPP** [29]	**ERI-3E**	**GCAM** [30]	**GEM-E3** [31]	**IMAGE** [32]	**MESSAGE** [33]	**PECE** [34]	**POLES** [35]	**WEM** [36]
Developer	National Institute for Environment Studies (NIES) Japan	Tsinghua University, China	Research Institute of Innovative Technology for the Earth (RITE) Japan	NCSC and Tsinghua University, China	Energy Research Institute (ERI) China	Pacific Northwest National Laboratory (PNNL), Richland, WA, USA	EU	PBL, The Hague, The Netherlands	International Institute for Applied Systems Analysis (IIASA), Laxenburg Austria	Renmin University and NCSC, Beijing, China	LEPII and IPTS, EU	International Energy Agency (IEA)
Region coverage	Global (32 regions)	National	Global (10 regions)	China	China	Global (32 regions)	Global (Flexible)	Global (26 regions)	Global (11 regions)	China	7 regions, 11 sub regions, 32 countries	Global (19 regions)
Time Horizon	2010–2050	2010–2050	2010–2100	2010–2050	2010–2050	2010–2100, five-year interval	NA	2010–2100, five-year interval	2010–2100, 10-year interval	2010–2050, five-year interval	Up to 2050, year by year	2012–2040, year by year
Base year	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010	2012
Model class	Recursive dynamic, partial equilibrium	Recursive dynamic, partial equilibrium	Dynamic non-linear optimization	Bottom-up non-linear technology optimization model	Unknown	Recursive dynamic, partial equilibrium	Recursive CGE	Recursive dynamic, Partial equilibrium	Dynamic linear Programming	Bottom-up non-linear technology optimization model	Simulation model, partial equilibrium	Simulation model, partial equilibrium
Objective function	Minimize annual cost	Minimize annual cost	Cost minimization	Supply-demand balance	Meet both development and environmental needs by cutting coal consumption	Minimize social costs	General Equilibirum	Minimize social costs	Minimization of the total discounted energy system costs	Minimization of the total discounted energy system costs	Supply-demand balance	Supply-demand balance
End-use sectors	Agriculture, transportation, rural, urban, commercial, industry	Industry, transportation, urban/rural residential, commercial	Demand including gaseous fuel, liquid fuel, solid fuel and electricity	Transportation, industry, building, agriculture	Urban/rural residential, commercial, industry, transportation	Industry, transportation, building	N/A	Heavy industry, transportation, residential, other (aggregated)	Transportation, residential, commercia industry	Transportation, industry, residential, agriculture,	Transportation, industry, residential, agriculture	Transportation, industry, building
Demands	Exogenous energy service demand by social economic parameters	Exogenously provided by Energy Service Demand Projection Model or endogenously driven by energy service marginal prices	Exogenously provided by historical data and IPCC SRES B2	Endogenous energy demand driven by social-economic parameters	Economic values transferred into product and service demand by STOCK model	Endogenous energy service demand driven by income and price	N/A	Endogenous energy service demand driven by income and other factors	Exogenous energy service demand from MEDEE-2 model	Energy service demand driven by social economic parameters (from PECE-ESD model)	Supply-demand balance Endogenous CES production function	Endogenous energy demand driven by socio-economic variables and end-user prices

Table A1. *Cont.*

Model	**AIM-Enduse** [26]	**China-MARKAL** [27]	**DNE-21** [28]	**DDPP** [29]	**ERI-3E**	**GCAM** [30]	**GEM-E3** [31]	**IMAGE** [32]	**MESSAGE** [33]	**PECE** [34]	**POLES** [35]	**WEM** [36]
Name of Selected Reference Scenario	EMF27-Base-FullTech	ROSECREF	AMPERE3-Base	N/A	Reference Scenario	AMPERE3-Base	AMPERE3-Base	AMPERE3-Base	AMPERE3-Base	AME Reference	AMPERE3-Base	Current Policy Scenario
Name of Selected Alternative Scenario [1]	EMF27-550-FullTech	ROSE 45-40-40	AMPERE3-550	China Deep Decarbonization Scenario (only one scenario)	Coal Cap Policy Scenario	AMPERE3-550	AMPERE3-550	AMPERE3-550	AMPERE3-55	CO_2 Price \$50 (5% p.a.)	AMPERE3-550	New Policy Scenario
Data Source	EMF27 Database [2]	RoSE Database [3]	AMPERE Database [4]	AMPERE Database [5]	China Coal Cap Study Project [6]	AMPERE Database [7]	AMPERE Database [8]	AMPERE Database [9]	AMPERE Database [10]	AME Database [11]	AMPERE Database [12]	WEO 2014 [13]

Note: Scenarios developed by the MIT-Tsinghua China Energy and Climate Project and the New Climate Economy Project are not included in this study because they are developed by the same team with DDPP with quite similar results. The aim of scenario comparison is to compare views from various modeling groups. Therefore, the two scenarios are excluded to maintain the balance. [1] Scenarios with the name "AMPERE3-550" are not 550 ppm scenarios for China, because the policy effort represented in this scenario is stronger than in the European Union or the United States. See Section 2.3; [2] International Institute for Applied Systems Analysis, EMF27 Database, 2012. Available at: https://secure.iiasa.ac.at/web-apps/ene/EMF27DB; [3] Unpublished data from the Roadmaps towards Sustainable Energy futures (RoSE) project. Data were acquired and analyzed by the authors. More information about Rose can be found at: http://www.rose-project.org/; [4,5,7–10,12] International Institute for Applied Systems Analysis, AMPERE Database, 2014. Available at: https://tntcat.iiasa.ac.at/AMPEREDB/; [6] Unpublished data from the China Coal Cap Project. Data were acquired and analyzed by authors. More information about China Coal Cap project can be found at: http://www.nrdc.cn/information?cid=49&chId=21; [11] International Institute for Applied Systems Analysis, AME Database, 2012. Available at: https://secure.iiasa.ac.at/web-apps/ene/AMEDB/; [13] International Energy Agency, 2014. World Energy Outlook 2014.

References

1. Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Farahani, E.; Kadner, S.; Seyboth, K.; Adler, A.; Baum, I.; Brunner, S.; Eickemeier, P.; et al. (Eds.) *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
2. Build Consensus and Implement Actions For a Cooperative and Win-Win Global Climate Governance System. Available online: http://www.fmprc.gov.cn/mfa_eng/wjdt_665385/zyjh_665391/t1194637.shtml (accessed on 21 November 2016).
3. Assessing Implementation of China's Climate Policies in the 12th Five-Year Period. Available online: http://www.wri.org/publication/assessing-implementation-chinas-climate-policies-12th-5-year-period (accessed on 21 November 2016).
4. Escalate Development Quality and Strengthen Actions to Address Climate Change. Available online: http://www.gov.cn/guowuyuan/2015-06/12/content_2878792.htm (accessed on 20 November 2015).
5. U.S.-China Joint Announcement on Climate Change. Available online: http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change (accessed on 21 November 2016).
6. Enhanced Actions on Climate Change: China's Intended Nationally Determined Contribution. Available online: http://www.ndrc.gov.cn/xwzx/xwfb/201506/W020150630783447810119.doc (accessed on 15 July 2015).
7. Liu, Z.; Guan, D.; Wei, W.; Davis, S.J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G.; et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **2015**, *524*, 335–338. [CrossRef] [PubMed]
8. Kaya, Y.; Yokobori, K. *Environment, Energy and Economy: Strategies for Sustainability*; Aspen Inst.: Washington, DC, USA; Brookings Institution: Washington, DC, USA, 1998.
9. Aldy, E.J. An environmental Kuznets curve analysis of U.S. state-level carbon dioxide emissions. *J. Environ. Dev.* **2005**, *14*, 48–72. [CrossRef]
10. Auffhammer, M.; Steinhauser, R. The future trajectory of US CO_2 emissions: The role of state vs. aggregate information. *J. Reg. Sci.* **2007**, *47*, 47–61. [CrossRef]
11. Burnett, J.W.; Bergstrom, J.C.; Wetzstein, M.E. Carbon dioxide emissions and economic growth in the U.S. *J. Policy Model.* **2013**, *35*, 1014–1028. [CrossRef]
12. Burnett, J.W.; Bergstrom, J.C.; Dorfman, J.H. A spatial panel data approach to estimating U.S. state-level energy emissions. *Energy Econ.* **2013**, *40*, 396–404. [CrossRef]
13. Nelson, J.P.; Kennedy, P.E. The use (and abuse) of meta-analysis in environmental and natural resource economics: An assessment. *Environ. Resour. Econ.* **2009**, *42*, 345–377. [CrossRef]
14. Stanley, T.D. Wheat from chaff: Meta-analysis as quantitative literature review. *J. Econ. Perspect.* **2001**, *15*, 131–150. [CrossRef]
15. He, J. Analysis of CO_2 emissions peak: China's objective and strategy. *Chin. J. Popul. Resour. Environ.* **2014**, *12*, 189–198. [CrossRef]
16. The World Bank Data. Countries and Economies. Available online: http://data.worldbank.org/country (accessed on 21 November 2016).
17. Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China. Available online: https://www.adb.org/sites/default/files/publication/175347/roadmap-ccs-prc.pdf (accessed on 21 November 2016).
18. An Analysis of China's INDC. Available online: http://www.ncsc.org.cn/article/yxcg/ir/201507/20150700001490.shtml (accessed on 15 September 2015).
19. United Nations. Department of Economic and Social Affairs. World Population Prospects, the 2012 Revision. Available online: http://www.un.org/en/development/desa/publications/world-population-prospects-the-2012-revision.html (accessed on 21 November 2016).
20. National Bureau of Statistics of China. National Database. Available online: http://data.stats.gov.cn/easyquery.htm?cn=C01 (accessed on 21 November 2016).
21. 2013 Energy Data. Energy Foundation: 2013. Available online: http://www.efchina.org/Attachments/Report/reports-20131212-zh/reports-20131212-zh (accessed on 15 September 2015).

22. China Statistical Year Book 2013. Available online: www.stats.gov.cn/tjsj/ndsj/2013/indexeh.htm (accessed on 21 November 2016).
23. National Bureau of Statistic of China. *China Statistical Abstract 2015*; China Statistics Press: Beijing, China, 2015.
24. Xu, G.; Jin, H.G.; Yang, Y.P.; Xu, Y.J.; Lin, H.; Duan, L.Q. A comprehensive techno-economic analysis method for power generation systems with CO_2 capture. *Int. J. Energy Res.* 2010; 34, 321–332.
25. The World Bank. *China 2030: Building a Modern, Harmonious, and Creative Society*; World Bank Publications: Washington, DC, USA, 2013.
26. Blanford, G.J.; Kriegler, E.; Tavoni, M. Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Clim. Chang.* **2014**, *123*, 383–396. [CrossRef]
27. Chen, W.; Wu, Z.; He, J.; Gao, P.; Xu, S. Carbon emission control strategies for china: A comparative study with partial and general equilibrium versions of the China MARKAL model. *Energy* **2007**, *32*, 59–72. [CrossRef]
28. Akimoto, K.; Tomoda, T.; Fujii, Y.; Yamaji, K. Assessment of global warming mitigation options with integrated assessment model DNE21. *Energy Econ.* **2004**, *26*, 635–653. [CrossRef]
29. Bataille, C.; Waisman, H.; Colombier, M.; Segafredo, L.; Williams, J.; Jotzo, F. The need for national deep decarbonization pathways for effective climate policy. *Clim. Policy* **2016**, *16* (Suppl. 1), S7–S26. [CrossRef]
30. Calvin, K.; Bond-Lamberty, B.; Clarke, L.; Edmonds, J.; Eom, J.; Hartin, C.; Kim, S.; Kyle, P.; Link, R.; Moss, R.; et al. The SSP4: A world of deepening inequality. *Glob. Environ. Chang.* **2017**. [CrossRef]
31. Capros, P.; Georgakopoulos, P.; Van Regemorter, D.; Proost, S.; Schmidt, T.; Conrad, K. The GEM-E3 general equilibrium model for the European Union. *Econ. Financ. Model.* **1997**, *4*, 51–160.
32. Kriegler, E.; Riahi, K.; Bauer, N.; Schanitz, J.; Petermann, N.; Bosetti, V.; Marcucci, A.; Otto, S.; Paroussos, L. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Chang.* **2015**, *90*, 24–44. [CrossRef]
33. Schwanitz, V.J. Evaluating integrated assessment models of global climate change. *Environ. Model. Softw.* **2013**, *50*, 120–131. [CrossRef]
34. Gritsevskyi, A.; Schrattenholzer, L. Costs of reducing carbon emissions: An integrated modeling framework approach. *Clim. Chang.* **2003**, *56*, 167–184. [CrossRef]
35. Clarke, L.; Krey, V.; Weyant, J.; Chaturvedi, V. Regional energy system variation in global models: Results from the Asian modeling exercise scenarios. *Energy Econ.* **2012**, *34*, S293–S305. [CrossRef]
36. Kesicki, F.; Yanagisawa, A. Modelling the potential for industrial energy efficiency in IEA's World Energy Outlook. *Energy Effic.* **2015**, *8*, 155–169. [CrossRef]