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Achieving China's Long-Term Carbon Emission Abatement Targets: A Perspective from Regional Disparity

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Received: 22 October 2018; Accepted: 14 November 2018; Published: 17 November 2018

Abstract: As China is the largest greenhouse gas emitter and has the characteristics of significant regional disparity, the issue of regional low-carbon development strategy is of vital importance for the achievement of the country's long-term emission targets. This work focused on China's long-term carbon emission abatement from the perspective of regional disparity. We firstly analyzed the national emission trajectories consistent with the current Intended Nationally Determined Contributions (INDCs), 2 °C, and 1.5 °C goals in two economic growth pathways by 2050 using a linear programming model, then classified the provinces into three categories, and compared results of different scenarios of regional disparity patterns, economic growth rates, and emission targets. Results showed that different regional patterns led to different required carbon reduction targets for all categories, and the regional emission reduction measures had to be stronger in a higher growth rate or a more stringent emission target, especially for the developed areas. A scheme of regionally coordinated low-carbon development was then recommended for the formulation of long-term regional emission targets, and carbon reduction strategies for categories were proposed in terms of energy mix optimization, industrial transformation, and technology innovation, which is of great policy implication for China in regional development and national emission targets enhancement.

Keywords: regional disparity; long-term emission target; carbon dioxide abatement; low-carbon development; China

1. Introduction

As climate change can induce great risk to human sustainable development, the Paris Agreement, adopted by parties of United Nations Framework Convention on Climate Change (UNFCCC) in 2015, proposed the goals to keep the global average temperature rise well below 2 °C relative to the pre-industrial level and pursue efforts to stay below 1.5 °C by 2100. Most of the countries have released their Intended Nationally Determined Contributions (INDCs) to reduce greenhouse gases (GHGs) and mitigate climate change. As the largest developing country and GHGs emitter, accounting for approximately 25% of global emissions [1], China promised in its INDCs to peak carbon emission around or earlier to 2030 and decrease its carbon emission per unit of GDP by 60–65% in 2030 compared to the 2005 level, which has attracted extensive attention worldwide. However, there is still a gap between current aggregated conditional INDCs and the 2 °C goal, let alone the 1.5 °C goal [2–4]. Most individual countries, including China, should further make their emission targets more ambitious and enhance abatement actions [5,6].

There have been many studies about China's carbon emission. On the national level, China's long-term carbon emission and low-carbon policy has attracted much attention due to its significance to the global reduction in recent years. Some investigations concluded that China's carbon emission would peak later than 2030 or even 2040 [7–9], while others focused on the feasibility of emission peak around 2030 [10–13] or earlier to 2030 [14–16], where the quantity and time of emission peak are mainly influenced by the magnitudes of policies adopted. Multiple measures were recommended in these studies to achieve emission targets, where energy structure optimization was particularly emphasized for deep de-carbonization transformation. However, there are still limited studies on China's long-term carbon reduction pathways concerning the Paris Agreement goals or total carbon emission quantity target, the most probable direction in which China's INDCs will be reinforced in the near future.

On the regional level, as China consists of areas with great differences in socioeconomic development and resource endowment, there exists evident and various regional disparities in carbon emission among areas. Differences of low-carbon development characteristics can be noticed among provinces or regions, such as decoupling relationships between carbon emission and economic growth [17], low-carbon economy efficiencies [18], and Environmental Kuznets Curve (EKC) effect [19]. Basic driving forces, such as economic growth, energy intensity, and energy structure [20,21], or other factors affecting carbon emission or energy consumption, such as urbanization, industrialization, foreign trade, and technology improvement, etc. were found to perform differently between regions [22–25]. Thus, carbon reduction potentials also varied between regions with different economic development and low-carbon characteristics [26,27]. Furthermore, carbon emission embodied in goods or electricity transfers among regions were also examined [28–31]. Accordingly, many studies suggested coordinating regional low-carbon development [19,21–23] or narrowing regional gaps by providing supports of finance, talents, and technology for less developed areas [32–34]. Emission target allocation is significant for regional low-carbon coordination, while the allocation result is influenced by methods and criteria adopted [35–39]. However, the investigations of regional low-carbon issues seldom concerned a long-term emission reduction strategy which could be greatly affected by regional disparity within the country.

As a result, it is necessary to conduct investigations integrating regional disparity and long-term low-carbon strategy consistent with the international climate goals, to address the climate change mitigation affairs of China from a regional perspective. Although some authors have briefly suggested that the developed areas should peak their carbon emissions earlier than others [40–42], there are still limited in-depth studies in terms of this. Hence, this work attempts to concentrate on the regionally coordinated carbon reduction pathway of China for the achievement of national long-term emission abatement responsibility, where several carbon emission drivers are analyzed and regional carbon reduction strategy is proposed for policy formulation.

2. Methods and Data

2.1. Basic Calculation and Data Sources

The Kaya identity [43] is applied for emission calculation in this work. This identity has been widely used in previous studies on national or regional carbon emissions because of its straightforward expression of carbon emission influencing factors and convenience in data collection. In this identity, as shown in Equation (1), carbon emission (CO_2) is decomposed into gross domestic products

(*GDP*, in Chinese yuan, CNY), total energy consumption per unit of GDP (energy intensity, *EI*), and carbon emission per unit of energy consumption (carbon intensity, *CI*), where *GDP* can be also further decomposed into permanent population (*Pop*) and per capita GDP (*PCG*). Based on the Kaya identity, the Logarithmic Mean Divisia Index method (LMDI) [44] is used to calculate the periodical contributions to the change of carbon emission of *GDP*, *EI*, and *CI*.

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

In this study, total energy consumption includes final energy consumption and energy loss during transformation, transition, distribution, storage, and other processes. Carbon emission is derived from primary fossil fuels combusted or lost inside the boundary of each province, with fuels used for raw materials excluded. Three basic types of fossil fuels are incorporated in emission calculation, namely total coal, total petroleum products, and (liquefied) natural gas (NG).

On the provincial level, socioeconomic data such as population and GDP are collected from the China Statistical Yearbooks. Energy consumption data are collected from the energy balance tables in the China Energy Statistical Yearbooks. On the national level, the quantities of these variables are the total amount of all provinces. Thirty provinces of mainland China are incorporated in the analyses, with Tibet excluded due to the lack of energy data and its minor quantity of estimated energy used compared to the country [45]. Low calorific values and carbon dioxide emission factors are used to transform fuel consumption to carbon emission. This work selects low calorific values recommended in the China Energy Statistical Year Book 2017, and carbon dioxide emission factors used for emission accounting by the government, i.e., 2.66, 1.76, and 1.59 $\mathrm{kgCO_2}$ per kilogram of standard coal equivalent ($\mathrm{kgCO_2/kgce}$) for coal, petroleum products, and NG, respectively.

According to China's national greenhouse gas inventory in 2012 [46], energy processes emitted around 88% of the total carbon emission. Most of the rest carbon dioxide was emitted by industrial processes in which non-metal mineral and metal products manufacturing accounted for a major proportion, while about half of the industrial process-derived emission could be neutralized by carbon sink effect from land-use change. Additionally, outputs of carbon-intense industries in China, such as cement and steel, will probably reach their peaks by around 2020 [14,47,48], which will effectively cease the increase of industrial process-derived carbon dioxide. Therefore, as the most important part of GHGs in China, only carbon dioxide emission from energy use will be incorporated in this work.

2.2. National Long-Term Emission Trajectory Analysis

Indicating the trends of carbon emission and Kaya items nationwide, the emission trajectories during 2015–2050 are analyzed under the targets of current INDCs, 2 °C, and 1.5 °C, the three target scenarios, respectively, by constructing a linear programming (LP) model. Comprising a series of decision variables, an objective function, and groups of constraints, this model enables the constrained trajectories when taking cost optimization criterion into account. Different from the methods used in previous studies, this model is based on the 'adverse forcing' mechanism, i.e., the final target being set at first and variables being solved constrained by necessary conditions, which can be used to examine impacts on the variables in a time series and help us set the targets of different stages. This model is suitable for our research with specific long-term abatement targets. The LP model is solved using the Solver tool added in Microsoft Excel 2010 software. In the Solver tool, the 'Simplex LP' solving method with default options is selected.

2.2.1. Decision Variables

The modified Kaya identity in Equation (2) can be rewritten in logarithmic form shown in Equation (3):

$$CO_{2,t} = GDP_t \times EI_t \times CI_t = GDP_0 \cdot \prod_{i=1}^{t} (1+g_i)^5 \times EI_0 \cdot \prod_{i=1}^{t} (1+e_i)^5 \times CI_0 \cdot \prod_{i=1}^{t} (1+c_i)^5 \tag{2}$$

$$ln\mathrm{CO}_{2,t} = ln\mathrm{CO}_{2,0} + 5\sum_{i=1}^{t} [ln(1+g_i) + ln(1+e_i) + ln(1+c_i)] \tag{3}$$

where g_i, e_i, and c_i are the average annual changing rates of *GDP*, *EI*, and *CI*, respectively, in the *i*-th five-year period (*i* = 1, 2, . . . , 7, denoted as P1, P2, . . . , P7, e.g., 2015–2020, 2020–2025, etc.) from 2015 to 2050, and the subscripts *0* and *t* denote the base year 2015 and the last year of the *i*-th five-year period, respectively. The Kaya identity is then linearized. The items $y_i = ln(1 + e_i)$ and $z_i = ln(1 + c_i)$ are selected as decision variables of the LP model, representing the optional magnitudes of energy saving and energy structure optimization, respectively, while GDP growth rates are fixed.

2.2.2. Objective Function

Overall decreasing range of carbon emission per unit of GDP can be interpreted as the totally social carbon abatement cost. Therefore, the objective function of the LP model can be the minimum decreasing range of carbon emission per unit of GDP throughout the research period (equal to maximum carbon emission in 2050) in view of cost minimization, as shown in Equation (4). The latest long-term outlook conducted by Organization for Economic Cooperation and Development (OECD) [49] serves as the fixed GDP growth rates. For contrast, another series of assumed higher growth rates is given referring to Reference [7]. The two growth scenarios are shown Table 1 and labeled by OECD and Fast, respectively.

$$\max\ ln\mathrm{CO}_{2,7} = ln\mathrm{CO}_{2,0} + 5\sum_{i=1}^{7} [ln(1+g_i)] + 5\sum_{i=1}^{7} (y_i + z_i) \tag{4}$$

Table 1. Average annual GDP growth rates (g_i) of the OECD outlook and the Fast growth scenarios.

Growth Scenario	2016–2020	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050
OECD	6.4%	4.8%	3.2%	2.7%	2.2%	1.8%	1.3%
Fast	6.5%	6.0%	5.5%	5.0%	4.5%	4.0%	3.5%

2.2.3. Long-Term Constraints

The current INDCs targets require peaking emission by 2030, i.e., zero emission growth after P3 (see Equation (5), the 'peaking constraints'), while the global 2 °C and 1.5 °C goals call for additional total quantity control objects analyzed as follows. According to the Fifth Assessment Report of IPCC [50], global GHGs emissions in 2050 are required to be cut down by 41–72% and 70–95% (the 10th to 90th percentile ranges) compared to 2010 for the likely achievement of 2 °C and 1.5 °C goals, respectively. In addition, China's fuel-combusted carbon emission accounted for 27.3% of the world in 2016, and the proportion has been stable and slightly decreasing since 2014 [51]. Hence, assuming that this proportion will further decrease to 20% by 2050 and that the global carbon dioxide emissions will be reduced by ranges the same as the total GHGs required by IPCC, the total carbon quantity control objects in 2050 should be decreasing by at least 63.3% and 87.3% compared to 2010 for the 2 °C and 1.5 °C goals, respectively, which is derived from the medians of the above required ranges (see Equation (6), the 'total quantity constraints').

$$ln(1+g_i) + y_i + z_i \le 0 \quad (i = 4,\ 5,\ 6,\ 7) \tag{5}$$

$$ln(R_{2010-2015}) + 5\sum_{i=1}^{7}[ln(1+g_i) + y_i + z_i] \leq \ln(1 - R_{reduc}) \tag{6}$$

where $R_{2010\text{–}2015}$ is the changing range of carbon emission during 2010–2015, and R_{reduc} is the required emission reduction range in 2050 compared to 2010 in the 2 °C or 1.5 °C goal.

2.2.4. Target Constraints

These constraints are about binding or projected targets declared by the Chinese government. The targets are decreasing ranges of carbon emission per unit of GDP (*Cgdp*) and energy consumption per unit of GDP (*EI*) during the 13th-Five-Year-Plan period (2016–2020) (greater than 18% and 15%, respectively), total energy consumption limited in 2020 (less than five billion tce), and carbon emission per unit of GDP in 2030 (decrease greater than 60% compared to 2005, the current INDCs target) (see Equations (7)–(10)).

$$5(y_1 + z_1) \leq ln\left(1 - R_{Cgdp,\ target,\ 2020}\right) \tag{7}$$

$$5y_1 \leq ln(1 - R_{EI,\ target,\ 2020}) \tag{8}$$

$$ln(Energy_0) + 5[ln(1+g_1) + y_1)] \leq ln\left(Energy_{target,\ 2020}\right) \tag{9}$$

$$5\sum_{i=1}^{3}(y_i + z_i) \leq ln\left(1 - R_{Cgdp,\ target,\ 2030}\right) \tag{10}$$

where the subscripts 'target' and the year mean the targeted energy consumption in the referred year, or targeted reduction range of *EI*/*CI* in the referred year compared to 2015.

2.2.5. Confining Constraints

A series of constraints are set to confine the changes of decision variables, rendering the results more justified. Firstly, all y_i and z_i should be minus, namely *EI* and *CI* should keep decreasing over time (see Equation (11), the 'minus constraints'). Secondly, some authors [52] synthetically analyzed a number of studies which used a variety of methods to investigate China's long-term carbon emission, providing ranges of normalized *EI* and *CI* in different years, which can be used as controlling ranges of *EI* and *CI* in our model (see Equation (12), the 'range constraints'). It should be noticed that when the LP model has no solution, only the controlling ranges of *CI* will be properly enlarged for available solutions. This is because deeper de-carbonization in energy structure is theoretically feasible by extensive use of carbon-free energies, while decreasing of *EI* is constrained over time by the limitation in energy saving technology improvement and industrial transformation [52]. Therefore, and thirdly, decreasing of *EI* would gradually slow down, while that of *CI* would gradually speed up in the research period, and which will be incorporated in the constraints (see Equation (13), the 'changing trend constraints'). Lastly, based on the changing trends of *EI* and *CI*, additional constraints incorporating three y_i and z_i in succession are considered to make the emission evolution more stable and smooth the whole emission trajectories (see Equation (14), the 'smoothing constraints').

$$y_i \leq 0,\ z_i \leq 0 \quad (i = 1, 2, \ldots 7) \tag{11}$$

$$ln(r_{EI,\ i,\ l}) \leq 5\sum_{j=1}^{i} y_j \leq ln(r_{EI,\ i,\ u}),\ ln(r_{CI,\ i,\ l}) \leq 5\sum_{j=1}^{i} z_j \leq ln(r_{CI,\ i,\ u}) \quad (i = 1, 2, \ldots, 7) \tag{12}$$

where the index r represents the ratio between *EI*/*CI* at the end of P_i and that of 2015, while its subscripts l and u denote the lower and upper bounds of the controlling ranges, respectively, derived from Reference [52]; the inequations mean the cumulative decreasing ranges of *EI*/*CI* should be confined in the controlling ranges in any period.

$$y_{i+1} \geq y_i,\ z_{i+1} \leq z_i \quad (i = 1, 2, \ldots, 6) \tag{13}$$

which is equal to 1 + $e_{i+1} \geq 1 + e_i$ and 1 + $c_{i+1} \leq 1 + c_i$, meaning that the reduction rate of *EI* (*CI*) in the latter period is less (greater) than the former.

$$y_{i-1} - y_i \leq y_i - y_{i+1},\ z_{i-1} - z_i \geq z_i - z_{i+1} \quad (i = 2, 3, \ldots, 6) \tag{14}$$

which is equal to $(1 + e_{i-1}) / (1 + e_i) \leq (1 + e_i) / (1 + e_{i+1}) \leq 1$ taking y_i as example, meaning that the periodical reduction rates of *EI* (*CI*) will sequentially become smaller (larger) in a smooth way.

2.3. Province Clustering and Disparity Analysis

The K-means clustering method, which has been used in previous China's provincial low-carbon studies [23,53], is employed by SPSS 16.0 software to create province categories based on their carbon emission characteristics. The clustering method can help us regionalize areas based on their characteristics, rather than spatial positions as adopted by many authors in their regional studies. The clustering method will present an effective regionalization scheme and be more appropriate and favorable to simulate regional disparity patterns.

Clustering indicators include *PCG*, *EI*, and *CI* in 2016, the items of Kaya identity except the scale-related *Pop*, indicating the levels of economic development, energy efficiency and industrial structure goodness, and energy consumption structure goodness, respectively. Besides, changing rates of these indicators during 2013–2016 are also incorporated in the clustering. The base year 2013 is selected because statistical provincial energy data since 2013 have been revised according to the Third National Economic Census held in 2013 and 2014, but they are incomparable with the previously published data. In addition, the 'new normal' development state of China, featuring lower rate and higher quality economic growth, started since around 2013 or 2014. Thus, the changing rates of these three indicators during 2013–2016 can represent their trends in the 'new normal' phase.

Provinces are then classified into several categories between which the overall differences of low-carbon development characteristics are significant. Each category will serve as a study object as a whole, and the clustering scheme will be the base of the following analyses and discussions. Certain disparity scenarios are then established on the basis of outlooks of long-term regional development patterns which depict the relative changing rates of *GDP*, *EI*, and *CI*. Combined with the analyzed national emission trajectories where the quantities of GDP, energy consumption, and carbon emission have been calculated, the regional emission trends are then derived and reduction strategies are discussed accordingly.

3. Results and Discussion

3.1. Outlook of National Long-Term Emission

Figure 1 displays the national trends of carbon emission and energy consumption in the two growth scenarios and the three target scenarios (labeled by Peak, 2 °C, and 1.5 °C, respectively). In particular, the controlling ranges of *CI* have been enlarged for available solutions of the LP model in the 2 °C and 1.5 °C target scenarios, indicating that in the long-term, energy structure adjustment should contribute more to carbon reduction than that confined in the initially narrower controlling ranges.

It is easy to notice that in the Peak target scenario (the red lines), both the carbon emissions and energy consumptions are much larger, while the limited total emission quantities significantly bend the curves in the 2 °C and 1.5 °C target scenarios and require earlier and smaller carbon peaks than the Peak target (the blue and green lines). Growth rate affects the shapes of curves as well. In the Fast growth scenario (the dashed lines), carbon emissions peak later with higher quantities, and energy consumptions are much larger than the OECD growth scenario (the full lines), which shows an obvious effect of lower growth rate on energy and carbon reduction. Moreover, in the 1.5 °C target scenario, the most stringent reduction requirement is consistent with the global reduction pathways recommended by the IPCC Special Report on Global Warming of 1.5 °C [54], implying that China has to take great responsibility and keep pace with the global reduction progress towards the 1.5 °C goal in the long term.

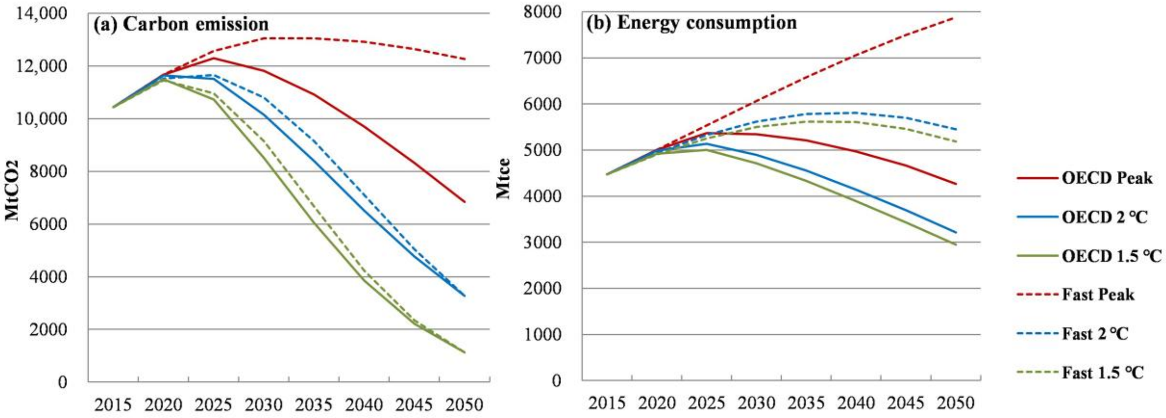

Figure 1. National (**a**) carbon emission and (**b**) energy consumption trends outlook: in the two growth scenarios and the three target scenarios.

3.2. Province Categories and Characteristics

The clustering scheme classifies provinces into three categories with evident characteristics. As shown in Figure 2, the eight provinces in Category 1 (C1) are those in the southeastern coastal areas along with Beijing and Tianjin, the two municipalities in north China; the seven provinces in Category 3 (C3) are located in north, northeast, and northwest China; Category 2 (C2) includes the left half of the provinces. Table 2 displays the clustering indicators of the three categories, showing significant differences between them.

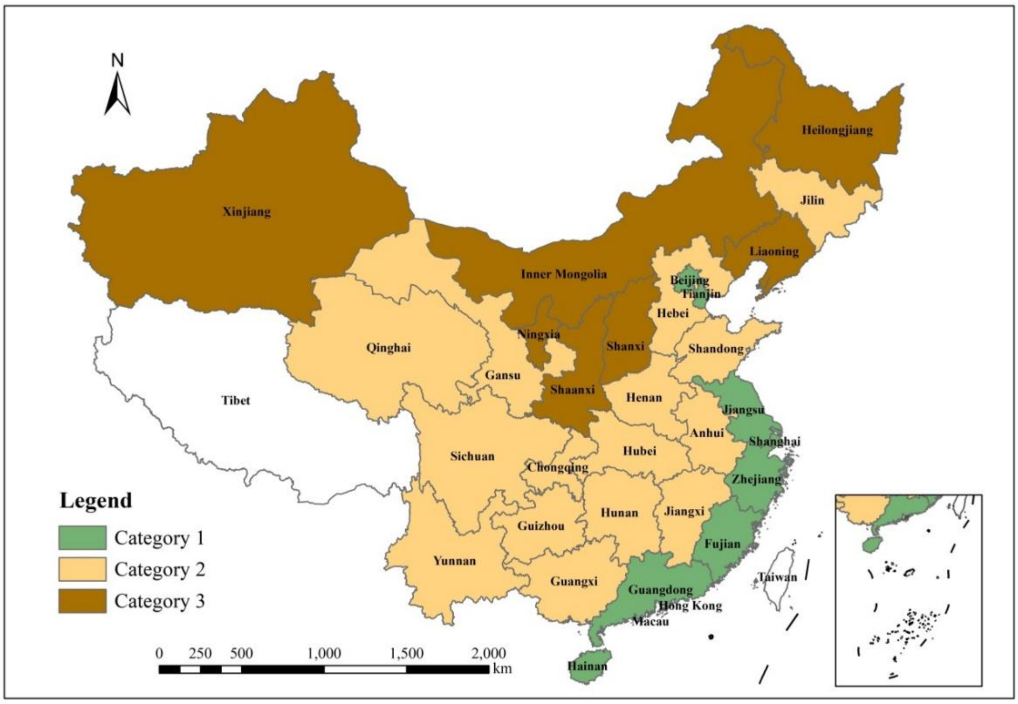

Figure 2. Province clustering scheme based on low-carbon characteristics.

Table 2. Integrated values of clustering variables for the three categories: per capita GDP, energy intensity, and carbon intensity in 2016, and their changing rates during 2013–2016.

Indicator	Value			Changing Rate		
	C1	C2	C3	C1	C2	C3
PCG (kCNY/capita)	87.3	45.5	47.5	23.2%	25.1%	16.6%
EI (kgce/kCNY)	39.9	61.4	105.1	−14.6%	−16.5%	−9.9%
CI ($kgCO_2$/kgce)	1.83	2.13	3.20	−7.5%	−7.3%	−1.7%

The *PCG* of C1 was noticeably higher than the other two categories and kept a relatively high growth rate in recent years, indicating both the higher level and potential of economic growth in these provinces. On the contrary, the *EI* and *CI* of C1 were significantly lower than the other two categories and decreased with a relatively high rate, indicating more optimized structure in both industries and energy use and higher potential of carbon reduction. Although the *PCG* of C2 was lower and *EI* and *CI* were higher than C1, their changing rates were close to C1, implying its economic development and carbon reduction were keeping pace with C1 in recent years. By contrast, the *EI* and *CI* of C3 were evidently high and showed slower decreasing rates than the other two categories, and the *PCG* grew with a relatively slow rate. It reveals that there are denser energy-intense and carbon-intense sectors in these provinces, and it also seems more difficult in adjusting economy and energy structure and keeping a higher growth rate.

3.3. Projection of Future Regional Disparity

To further reveal the characteristics of categories and analyze the regional development pattern, additional indicators for each category are shown in Table 3. Urbanization rate and tertiary industry shares are given for the years 2000, 2013, and 2016, between which are approximately the periods of 'economy take-off' and 'new normal' for China, respectively. Changing ranges of energy related quantities (total energy, primary energy types, and carbon emission) during 2013–2016 are also shown.

Table 3. Additional socioeconomic indicators and changes of energy related quantities for the three categories.

Indicator Set	Indicator	Year	C1	C2	C3
Socioeconomic indicators	Urbanization rate (%)	2000	52.1	29.8	42.5
		2013	68.4	47.7	56.0
		2016	70.5	52.2	58.6
	Tertiary industry share of GDP (%)	2000	41.1	35.1	36.6
		2013	49.7	37.5	38.2
		2016	54.7	44.4	48.5
Changes of energy related quantities (%)	Coal consumption	during 2013–2016	−6.9	−4.5	5.4
	Petroleum consumption		10.9	17.3	2.7
	Natural gas consumption		36.7	28.3	8.8
	Primary power generation		72.7	38.9	55.3
	Total energy consumption		7.5	6.3	6.1
	Carbon emission		−0.5	−1.4	4.3

Category 1 represents the generally most developed areas which benefit greatly from the 'reform and opening-up policy' in the last several decades. Beginning from the 1980s, processes of economic development, industrialization, and urbanization were boosted in these areas and kept advanced, which can be illustrated by the *PCG*, tertiary industry share, and urbanization rate, respectively. Thus, these areas have also attracted people to immigrate and account for an increasing proportion of population countrywide (from 23.1% in 2000 to 25.8% in 2016). On the other hand, these areas have highly regarded and better implemented policies of economic transformation, energy saving, and environmental protection ever since, because they confronted the problems of both economic transformation and environmental pollution at the earliest, and had higher capacity to address these problems, so that their *EI* and *CI* were the lowest. In recent years, although the total energy consumption increased the most quickly, these areas reduced coal consumption and increased the low-carbon and pollutant-free natural gas as well as primary power consumption the most evidently, enabling the highest decreasing rate of *CI*. Although areas of C1 are the most developed within the country, their urbanization rate and tertiary industry share are still low compared to major developed countries, implying they still have great space for urbanization and growth of modern industries, such as service, high-tech, and high value-added industries. Accordingly, the Chinese central government has formulated relevant regional development projects in recent years, such as 'Coordinated Development of Beijing Tianjin and Hebei Province', 'Yangtze River Delta Metropolitan Area Development' (covering Shanghai, Jiangsu, and Zhejiang Provinces), 'Guangdong-Hong Kong-Macau Greater Bay Area Development', and 'Hainan Free Grade Port Construction', etc., which will continue to greatly promote the processes of modernization, as well as the reinforcement and perfection of ecological civilization regulations in these areas.

Category 2 and Category 3 can be regarded as the under-development areas due to their lower GDP per capita compared to Category 1, but other characteristics indicate great differences between them. As for provinces of C3, they are rich in natural resources, such as coal, petroleum, iron and other mines, and developed dense manufacturing, especially heavy and energy-intense industries in an early time, and the economic growth and urbanization process were also boosted earlier than C2. As a result, their socioeconomic indicators were not the smallest, but the energy intensity and carbon intensity were the highest among all categories, accompanied by difficulty in economic transformation and energy structure optimization called the 'carbon lock-in' effect. This effect may be the cause of the continuously growing coal consumption and carbon emission. In addition, as China entered the 'new normal' phase, the limited demand for heavy industrial products partly led to the decline of the output of secondary industry in most areas of C3, which in turn raised its share of tertiary industry evidently. As for provinces of C2, although they were the least developed in 2000, the gap between C2 and C3 was narrowed since then because of its rapid development, as illustrated by the significantly increased per capita GDP, urbanization rate, and tertiary industry share. In addition, to some extent, they developed in a more low-carbon way different from C3, because their *EI* and *CI* were lower and more rapidly decreased in recent years. In detail, areas of C2 showed significant effect in primary energy structure adjustment during 2013–2016, with decreasing coal and rapid growth in natural gas consumptions.

On the basis of the regional disparity analysis, three regional disparity scenarios are established as shown in Table 4. Regional disparity scenarios consist of relative GDP growth rates, *EI* reducing rates, and *CI* reducing rates which denote the changing rates of each category compared to those of C2, as C2 accounts for the major parts of the nation's GDP, energy consumption, and carbon emission. For Scenario 1 (S1), called the 'Current State Continuation' and as a reference scenario, these relative changing rates are derived from those during 2013–2016, assuming that the long-term regional disparity trend will be consistent with the recent 'new normal' state. Scenario 2 (S2) assumes that the developed areas C1 will grow more rapidly than C2, implying C1 will continuously concentrate economic outputs and population, as well as make greater efforts to reduce both energy and carbon intensity and keep higher decreasing rates. Therefore, it is called the 'Developed Areas Prior' scenario. Meanwhile in this scenario, we consider the gaps between the changing rates of *GDP*, *EI*, and *CI* of C3 and C2 are smaller compared to S1. Scenario 3 (S3), called the 'Advanced Techniques Utilization' scenario, assumes that advanced techniques of energy saving and energy substitution for energy- and carbon-intense sectors are widely applicable, so that the areas of C3 who have great carbon reduction potentials will decrease their *EI* and *CI* more significantly compared to S2. Figure 3 shows the emission trajectories which are all normalized by the emissions in 2015 for the three categories, in all regional disparity and target scenarios and in the OECD growth pathway, with the nation's trends presented for comparison. As for the Fast growth scenario, the relative locations of each curve are similar to this.

Table 4. Regional disparity scenarios: long-term relative changing rates of *GDP*, *EI*, and *CI* for the three categories.

Regional Disparity Scenario	Category	Relative Changing Rate [1]		
		GDP	*EI*	*CI*
S1: Current State Continuation	C1	0.95	0.90	1.05
	C2	1.00	1.00	1.00
	C3	0.70	0.60	0.40
S2: Developed Areas Prior	C1	1.10	1.20	1.20
	C2	1.00	1.00	1.00
	C3	0.90	0.80	0.60
S3: Advanced Techniques Utilization	C1	1.10	1.20	1.20
	C2	1.00	1.00	1.00
	C3	0.90	1.10	1.10

[1] The relative changing rates of C2 are fixed at 1, and those of C1 and C3 represent the relative changing speeds compared to C2. The actual changing rates of each category are calculated according to the nation's total GDP, energy consumption, and carbon emission.

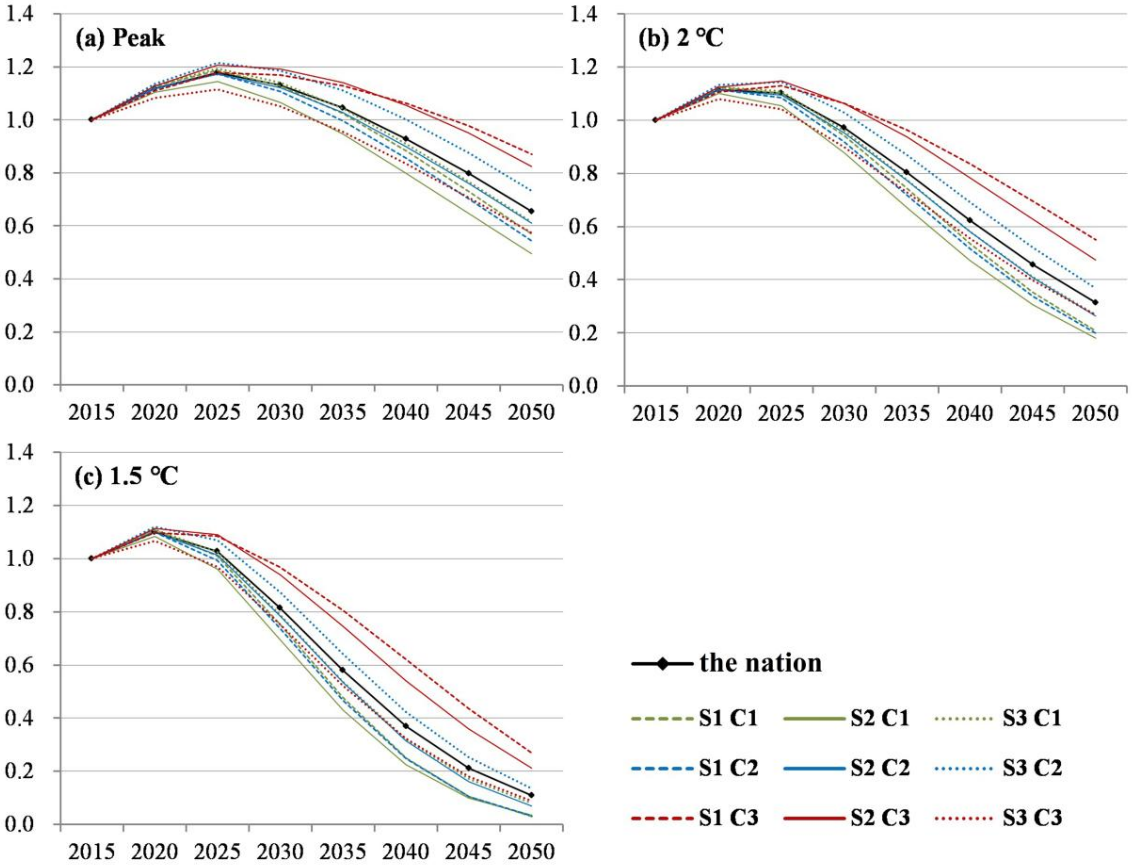

Figure 3. Normalized carbon emission trajectories of each category: in the OECD growth pathway and the three regional disparity scenarios, for the (**a**) Peak, (**b**) 2 °C, and (**c**) 1.5 °C targets, respectively.

3.4. Scenario Comparisons and Uncertainties

3.4.1. Regional Development Pattern

Different regional development patterns will result in different carbon emission trajectories for each province category on the basis of the clustering scheme. As shown in Figure 3, the C3 curves in S1 and S2 (the red dashed and red full lines) are obviously high in all target scenarios, but those in S3 (the red dotted lines) are beneath the nation's curves and peak earlier than the other two disparity scenarios because of the higher *EI* and *CI* decreasing rates. Especially in the S1 pattern, the decreasing rates of *EI* and *CI* of C3 are obviously less than the other two categories, leading to an extending gap of reduction ranges over time. By contrast, all the C1 curves (green lines) are beneath the nation's curves, as the developed areas should take heavier reduction responsibility. In the 1.5 °C target of S1 or S2 in particular, areas of C1 will reduce carbon emission to a near zero-carbon state by 2050, which is of significant policy implication since the developed areas have to act as pioneers to depress their emissions for the achievement of 1.5 °C goal.

As socioeconomic development of China is in an adjusting stage in recent years, regional development pattern is of special characteristics in the 'new normal' phase. The developed areas have been experiencing a deep transformation process and growing with a relatively lower speed, which has also occurred similarly in many developed countries. The energy- and carbon-intense areas have encountered more difficulty in keeping rapid growth and adjusting industrial structure. In contrast, other areas as included in C2 have been developing relatively well with higher growth rate and energy intensity decreasing rate as well as rapider urbanization process, due to their backwardness advantages in regional development. However, this regional development pattern, i.e., relative changing rates of the variables, may probably evolve as socioeconomic transformation is processed countrywide in the long term. The developed areas (C1) are likely to grow more rapidly based on the increasingly concentrated population and economy, which has occurred in many other countries. These areas will also implement the strongest carbon reducing measures due to the most stringent ecological civilization regulations. As well, the lag in economic growth of C3 compared to the other two categories is likely shrink due to the occurrence of gradual adjustment in industry and release of growing potential and momentum. However, considering the principally high-carbon characteristics of energy utilization in the C3 areas, as well as the great uncertainty in advanced de-carbonization technology availability, their *EI* and *CI* decreasing rates will be still lower than the other two categories over time, as conservatively estimated.

Accordingly, S2 will be the most likely regional pattern in the three given disparity scenarios. It should be noticed that there are still great uncertainties in regional development trend because of the differences between categories in many other dimensions, such as population, resources, environment, and ecology. Moreover, evident variation can be easily noticed within a category, which also increases uncertainties in regional disparity prediction. Focusing on S2, Figure 4 shows the five-year periodical effects of the three Kaya items and the total effects, for further examining the differences of carbon emission drivers among all target and growth scenarios for the three categories. The effect here denotes the contribution of a driving force to the increase or decrease of carbon emission during a period.

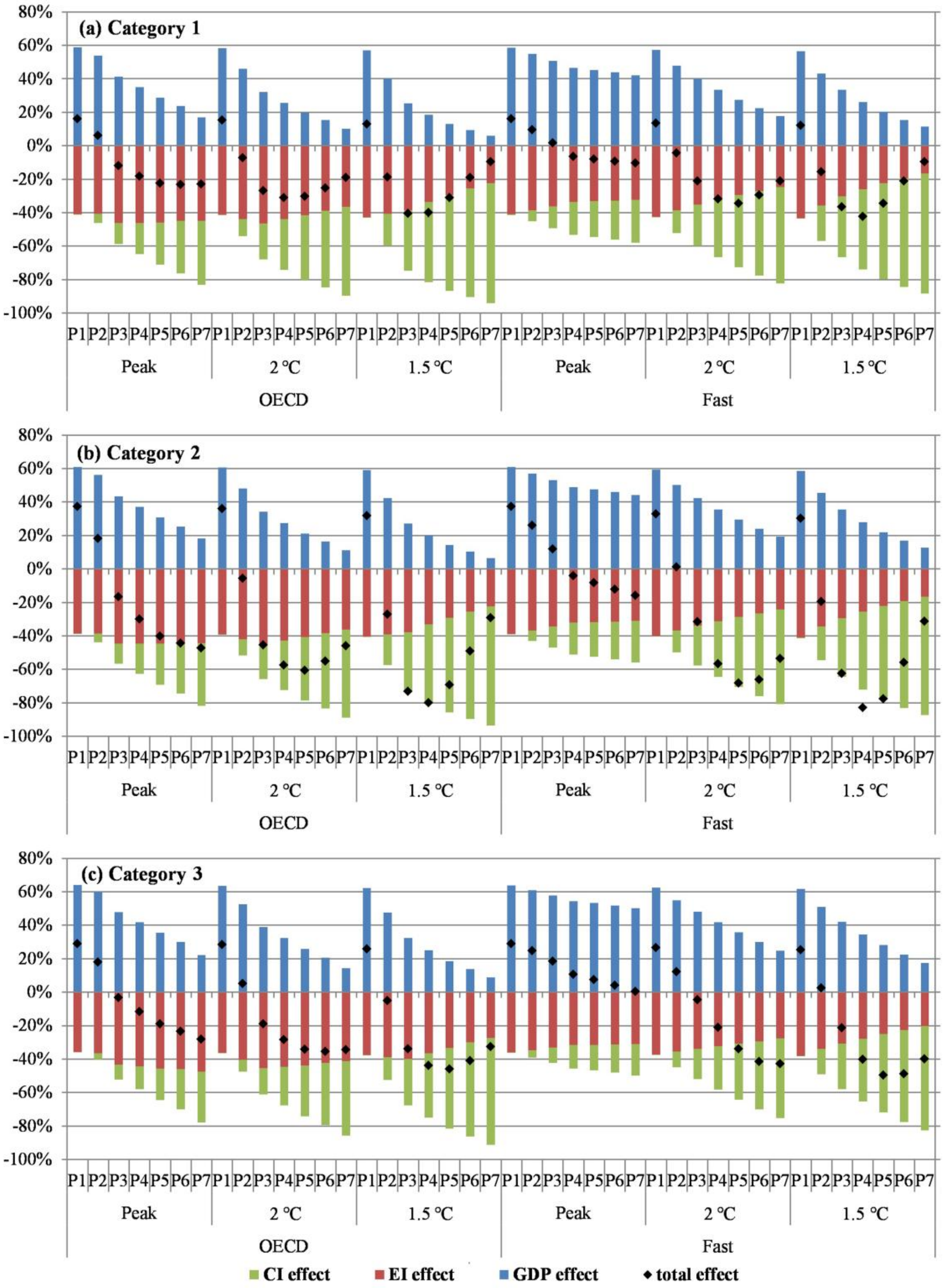

Figure 4. Periodical effects of the three basic driving forces (in percentage, stacked bars referring to the left axis) and the total (in quantity, black dots referring to the right axis) on carbon emission: in all target and growth scenarios of Scenario 2 'Developed Areas Prior' for (**a**) Category 1, (**b**) Category 2, and (**c**) Category 3. The effect in percentage denotes the ratio of the signed quantity to the stacked-up absolute quantities.

3.4.2. Economic Growth

As economic growth is the most important driving force in increasing carbon emission, the GDP effect is much more significant in increasing emission in the Fast scenario. Higher economic growth results in the requirement for more reinforced measures to cut down the induced emission growth.

Economic growth also affects the carbon emission peak time where the black dots shift from above zero to below zero in Figure 4. This is particularly obvious for the current INDCs target (Peak scenario) where the three categories peak their carbon emission around 2025 in the OECD growth pathway, while in the Fast growth scenario C1 and C2 peak around 2030 and C3 keeps increasing emission by 2050.

Since the 'reform and opening-up policy' implemented in 1980s, China has experienced several radical changes in economic growth. After joining the WTO in the early time of the last decade, manufacturing and commerce development, urbanization, and infrastructure construction blossomed in China, and then carbon emission rose drastically along with GDP growth. Afterwards, in the 'new normal' phase, GDP growth rate dropped from the high speed to a median-to-high speed, which is resulted from complicated factors. As China's economic growth is synthetically influenced by conditions of foreign trade, demographics, technology innovation, and further reform practices, etc., it is of great uncertainty to accurately project the future, especially long-term economic growth tendency of China. But it is foreseeable that China will drop its growth speed gradually along with the further economic development process, which is similar to many other developed countries, as predicted by OECD.

3.4.3. Emission Target

As the emission target becomes more stringent (from Peak to 2 °C and 1.5 °C), the *CI* effect on emission change is more significant compared to *EI* effect for all categories, due to the larger potential of energy structure optimization that can contribute more to carbon reduction. The enhancement of the emission target also affects the peak time to different extents for each category, which is especially easily noticed in the Fast growth scenario. In addition, the appearances of maximum minus total effect which is also the inflection point of an emission curve, are differentiated between emission targets. Figure 4 shows that a more stringent target for each category requires an earlier inflection point, i.e., earlier release of maximum emission reduction potential.

As China's current INDCs can hardly satisfy the goals proposed by Paris Agreement, they will probably be reinforced to be consistent with the 2 °C goal or even the 1.5 °C goal in the near future, although the target adjustment is related to global economic and technological development, negotiation between governments, or even shift in the cognition of climate change. The INDCs reinforcement may include earlier peak time, total quantity controlling, or even incorporation of other GHGs, which is much more stringent than the current ones. As a result, it is of vital implication to encourage local governments to schedule deeper abatement policy in advance, especially for the developed areas who should take the lead in deep de-carbonization.

3.4.4. Technology Improvement

Technology improvement is quite important to carbon emission reduction, as it can potentially decrease the cost and expand the use of renewable or non-conventional energies. There are many approaches of energy substitution. In China, coal accounts for over 60% of the total primary energy consumption, and coal-fired electricity accounts for nearly 70% of the total power generation in 2016, implying substitution of coal should be emphasized to greatly decrease *CI* in the long term supported by cleaner power and fuel technology innovation. In terms of power generation, cost saving, and efficiency promotion, nuclear, solar, and wind powers are key to widely substituting coal-fired electricity. In terms of final use, coal combustion can be replaced by natural gas, biofuels, or electricity in manufacturing and living, where the decrease of cost of the substituting facility and energy used is the most essential. In addition, the transportation sector is a most important carbon emitter for its large oil consumption, and electrification can significantly help reduce emission. Innovative energy utilizations, such as marine, geothermal, or even nuclear fusion power, also deserve attention for their considerable potential in energy substitution.

However, energy technology innovation is of great uncertainty, depending on the inputs of intelligence and funding into research and development activities. On the other hand, as implied by the solutions of the LP model, *CI* should decrease more significantly after 2025 (refer to Figure 5), and should be cut down by a huge range by 2050 compared to 2015 (56% and 84% for 2 °C and 1.5 °C targets, respectively, in OECD scenario; 74% and 91% for 2 °C and 1.5 °C targets, respectively, in Fast scenario; it is equal to that at least 70% of the primary coal consumption is substituted by carbon-free energies, based on the energy structure in 2015). As a result, sustaining and sufficient support is necessary to ensure the availability of energy substitution technologies among which coal substitution is the most important for the achievement of significant *CI* reduction. Moreover, Energy saving techniques in all sectors are favorable to slow down the growth of energy use and reduce energy intensity, and wide use of CCUS technology is important for reducing carbon emission derived from fuel combustion, which also deserves attention in the long term.

3.5. Low-Carbon Strategies for Each Category

It is essential to set long-term regional emission targets consistent with national abatement requirements. The emission trajectories for the three categories, which are in the most likely OECD growth, 2 °C target, and 'Developed Areas Prior' pattern scenarios, are recommended to provide a framework to address regional carbon reduction policy making. Figure 5 shows the evolving indicators of the recommended areal emission trajectories, including GDP, energy consumption, carbon emission, energy intensity, and carbon intensity. It can be observed that the recommended trajectories require the peaking of national emission during 2020–2025, with C1 and C2 peaking simultaneously and C3 peaking later. The peaking of energy consumption will come around 2025 for all categories. Long-term carbon emission reduction strategies for each category are then proposed.

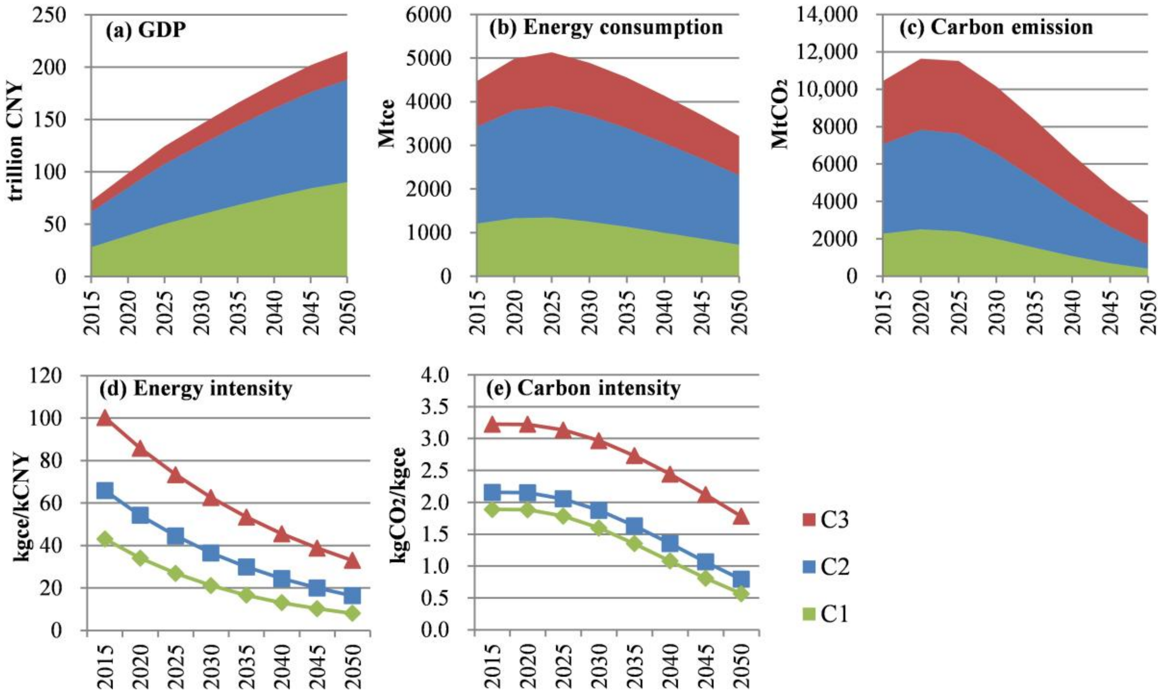

Figure 5. By-category (**a**) GDP, (**b**) energy consumption, (**c**) carbon emission, (**d**) energy intensity, and (**e**) carbon intensity of the recommended emission trajectories: in the compound scenario of the OECD growth pathway, 2 °C target, and 'Developed Areas Prior' regional disparity patterns.

For Category 1 involving the developed areas, the largest decreasing ranges in *EI* and *CI* must be achieved. It is essential to implement strong policies to significantly reduce carbon emission with sufficient financial and technical support due to these regions' huge historical cumulative emissions.

Firstly, as for power supply, multiple types of carbon-free power should be popularized widely in these areas to cover the existing and growing power demand. Nuclear power is the most important in power generation de-carbonization because of its stable and vast electricity supply capacity and suitable conditions for construction in these areas, and it should be popularized as early as possible due to its long construction period. Coal-fired power plants with low efficiency have to be closed in the near future and newly built coal-fired power units should be strictly forbidden, while gas-fired power generation popularization should be intensified. Secondly, as for final energy use, building and transportation are important consumption-based emission and carbon reduction sectors induced by intense urbanization. Green and low-carbon building should be widely implemented in both newly built and existing buildings for energy saving. It is also important to substitute conventional petroleum-based vehicles with electric or energy-saving ones. New energy utilization, such as a distributed energy system integrating solar, wind, and gas power, etc., should be also vigorously promoted in urban communities and industrial parks. Thirdly, as for industrial development, high-tech and high value-added industries should be given priority to develop in these areas, and existing energy-inefficient industries should be eliminated, leading to a further economic transformation and energy intensity decrease. Lastly, as for technology innovation, these areas should strongly encourage research, development, and application of innovative energy technology, such as energy storage, intelligent energy systems, and energy saving, etc., to take the lead in technology reformation and popularization.

For Category 2, median decreasing ranges of *EI* and *CI* are required following C1. In terms of industrial development, it is suggested for these areas to avoid the high-carbon industrialization route, i.e. driving economic growth by developing energy- and pollution-intense industries, to control the potentially quickly growing energy consumption and carbon emission in the subsequent development process. As the major under-developed areas, they need acceleration of industrialization for sustainable socioeconomic development, but only those industries of advanced techniques can be encouraged. The existing inefficient productivities should be restricted and weeded out step by step. Low-carbon sectors, such as the service industry, tourism, and advanced manufacturing, should be encouraged. In terms of energy use, these areas should take full advantage of non-fossil energy potentials depending on the local resource endowment, and reduce coal consumption in both power generation and final use. One of the most important practices is to ensure and promote the absorption of renewable electricity by grids, especially hydraulic power, by proper supports and perfection of renewable energy encouraging policies. As well, it is necessary to increase the cost of coal utilization in these areas by financial measures to restrain coal consumption.

For Category 3, the carbon-intense areas, it is recommended that they shoulder a weaker carbon reduction burden, due to their industrial development foundation and resource endowment. Firstly, these areas can reserve energy-intense sectors, but have to implement stringent energy saving and efficiency improving measures which would be an important driver to decrease energy intensity required by the recommended trajectory, as the energy-intense sectors generally have higher energy reducing potentials. Secondly, as these areas are abundant in renewable energy resources, principally solar and wind, as well as being relatively rich in land resource, they should make greater efforts to develop large-scale renewable energy generation systems. Similar to C2, these renewable powers should be supported by valid policies for their efficient utilization. Thirdly, coal-fired power generation should be also restrained to give space to renewables, and to mitigate or even eliminate the 'carbon lock-in' effect.

4. Conclusions

This work focused on the future carbon emissions of different areas in China by investigating multiple scenarios based on the national emission trajectory analysis and put forward strategic suggestions on regional low-carbon development. It is found that stronger measures and earlier release of reduction potential are required in the scenarios of rapider economic growth and more stringent emission targets compared to the current INDCs for all areas, and regional disparity patterns obviously affect the relative carbon reduction ranges among categories. Based on the discussion on the likelihood of multiple scenarios, the emission trajectories of each category in the 2 °C target, OECD growth outlook, and 'Developed Areas Prior' disparity pattern scenarios are then recommended as the long-term regional emission targets. According to the comparisons between scenarios and the recommended emission trajectories, some strategic suggestions are proposed as follows, which can practically help China form its long-term carbon abatement strategies for effective mitigation of climate change.

- In terms of energy use, the developed areas have to take the lead in popularization of non-fossil energies (nuclear power in particular), substituting the coal-fired power plants, and utilizing innovative energy technology at a large scale to accelerate the energy substitution process in the industrial, building, and transportation sectors. The central and western under-developed areas should encourage energy structure optimization by multiple measures. By contrast, the currently high-carbon areas can take a weaker energy de-carbonization burden, with effective renewable energy use as preferable measure.
- In terms of industrial development, deep economic transformation should be motivated in the eastern developed areas by encouraging high-tech and high value-added industries as well as eliminating energy-inefficient and carbon-intense sectors. Most of the central and western under-developed areas should continue to grow in a more low-carbon way by developing energy-efficient manufacturing and service industries as well as restricting carbon-intense sectors. As for the northern carbon-intense areas, priority should be given to energy saving and efficiency improving in the existing high-carbon industries.
- Finally, it is strongly suggested that China should formulate long-term regional reduction targets and strategies in advance. These targets will be important for the provinces to plan their long-term emission pathways as early as possible. Moreover, technology improvement should be also promoted as early as possible for the achievement of significant countrywide carbon reduction by 2050, especially for the developed areas who should take the lead in technology innovation.

Author Contributions: Conceptualization, Y.B.; Formal analysis, Y.B.; Funding acquisition, X.Z.; Investigation, Y.B.; Methodology, Y.B.; Project administration, X.Z.; Supervision, Z.Y.; Validation, J.F. and C.H.; Writing—original draft, Y.B.; Writing—review & editing, J.F. and C.H.

Funding: This research was funded by the Special Fund for Low Carbon Development of Guangdong Province, grant number NC-2016-170P.

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

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