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The policy-driven peak and reduction of China's carbon emissions

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Abstract

Pursuant to the Paris Agreement, China committed itself to peak its carbon emissions by around 2030 and to increase the non-fossil share of primary energy to 20% at the same time. The government has supported the international agreement by setting and strengthening the domestic policy targets for an earlier peak and faster reduction, aiming to contain the average global temperature increase to well below 2 °C. We develop a Kaya Inequality method to assess the time of peak and pace of reduction of China's energy-related CO_2 emissions based on the national energy policy targets for 2030. We find that, despite the minor fluctuations, the current plateau essentially represents the peak emissions and should enter a phase of steady decline by around 2025, given current trends in energy consumption and decarbonization. Such developments would be consistent with the strengthened national policy target to achieve 50% of renewable power generation by 2030. However, the basic policy targets − a 20% share of non-fossil energy and 6 Gtce in total energy consumption by 2030 − would be insufficient to peak carbon emissions by around 2030. The synergy and interplay between domestic policy target setting and international climate commitments shed light on the need to elevate national climate ambitions under the Paris Agreement and beyond.

Keywords: China's carbon peak; Paris agreement; Reduced Kaya approach; Climate change

1. Introduction

As the largest national emitter of greenhouse gases, China committed itself under the Paris Agreement to reach carbon emissions peak by around 2030 and, in the meanwhile, to increase the non-fossil share of its primary energy to 20%. The time and size of peak and the pace of reduction of China's emissions are critically important to the international goal of limiting global temperature increase, especially when the USA, the world's second largest emitter, has decided not to cooperate with the international accord (Kemp, 2017). In the Anthropocene, the actions of nation states are key drivers of changes in the Earth system (Goodwin et al., 2018; Lewis and Maslin, 2015). Far-reaching national policies by the largest players may become triggers and even fundamental factors in shaping the future of the social-natural systems in which all humanity lives, particularly in a time with a multitude of

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political, social, economic and physical uncertainties (Convery and Wagner, 2015; Stern, 2007, 2015).

The Chinese government has supported the Paris Agreement and adhered to its Nationally Determined Contribution (NDC) by setting and strengthening domestic policy targets in order to reach an earlier peak and achieve faster reduction, in line with the agreed-upon need to contain the average global temperature increase to well below 2 °C (Elzen and Höhne, 2010; Millar et al., 2017; Rogelj et al., 2016). Within weeks of the Paris Agreement taking effect in 2016, the Chinese government issued the National Strategy on Energy Production and Consumption Revolution (2016–2030), specifying its targets for energy consumption and non-fossil energy by 2030 (NDRC, 2016).

Chinese energy and environmental policies have delivered encouraging results so far: the coal cap policy for air pollution control, combined with economic deceleration and clean energy development, has likely already led to a peak in coal consumption in 2013, at least seven years earlier than expected (Qi et al., 2016). Meanwhile, the energy intensity of the economy has decreased by more than 45% since 2005, meeting China's Copenhagen (COP15, 2009) target for 2020 three years earlier than promised. The target for non-fossil share of primary energy consumption is also on track. The credibility of the targets is supported by the system of policy implementation. When policy targets are set as restrictive by the central government, they are taken as binding at all levels of local governments and are consequently implemented by relevant administrative units and enterprises (Qi and Wu, 2013). Historically, China has a track record of consistently achieving its energy policy targets, especially with respect to energy efficiency (Qi et al., 2013).

Various data sources have shown that China's energy-related carbon emissions may have reached a plateau with minor fluctuations since 2014 (Qi, 2017; Qi and Lu, 2018). Its projected carbon peak has been examined using different simulation models, and the modeled peaking time has generally fallen between 2020 and 2030 (Elzen et al., 2016; Green and Stern, 2016; Jackson et al., 2015; Jiang et al., 2016, 2013; Liu et al., 2017; Peters et al., 2017, 2015). These conventional assessments of emissions peak are based on a bottom-up modeling approach, the emissions calculated with variables from the Kaya decomposition. This approach entails assumptions about future economic growth, industrial structure, technology, energy structure, and additional details about social-economic factors (Peters et al., 2017), each with a great deal of uncertainty. The high degree of freedom to adjust the variables and the uncertainty associated with each variable make it difficult to assess the credibility of both the modelling and the range of carbon emissions estimates.

In this study, we address these challenges in climate policy research by making two important contributions. First, we develop a novel approach to assess the peaking time and pace of reduction of China's carbon emissions based on credible national policy targets, by transforming the static Kaya Identity to a dynamic Kaya Inequality Model. This method can reduce the uncertainty of prediction by incorporating national policy targets. Second, using the Kaya Inequality Model, we estimate China's carbon emissions peak and reduction under different scenarios of energy consumption and carbon intensity, providing decision-makers, stakeholders, and researchers with relevant information on the implications of different energy policies.

2. Methodology and data

2.1. Reduced Kaya approach

Conventional Kaya Identities are used to assess carbon emissions (Kaya, 1990). Kaya Identity can be reduced to include two terms, energy consumption and carbon intensity of energy:

$$C = E \times \frac{C}{E} = E \times CI \tag{1}$$

where C is energy-related CO_2 emissions, E is total primary energy use (fossil and non-fossil fuels), and CI is the carbon emissions per unit energy use (carbon intensity of energy).

2.2. Decomposition

We perform Index Decomposition Analysis in this study since we don't aim to assess structural changes. When we consider the interaction terms separated, the change rate of carbon emissions can be determined by these formulae:

$$\frac{\mathrm{d}C}{C} = \frac{\mathrm{d}(E \times CI)}{E \times CI} \tag{2}$$

$$\frac{\mathrm{d}C}{C} = \frac{\mathrm{d}E \times CI + E \times \mathrm{d}CI}{E \times CI} \tag{3}$$

$$\frac{\mathrm{d}C}{C} = \frac{\mathrm{d}E}{E} + \frac{\mathrm{d}Cl}{CI} \tag{4}$$

2.3. Kaya Inequality

Each term is the standard annual growth rate (%) of each factor and the magnitude of the interaction term can be isolated to assess its implications. Since our approach is most relevant for historical and short-to medium-term trends, then, Eq. (4) can be transformed into:

$$\frac{\Delta C}{C} \approx \frac{\Delta E}{E} + \frac{\Delta CI}{CI} \tag{5}$$

Let $r_E = \frac{\Delta E}{E}$ and $r_{CI} = \frac{\Delta CI}{CI}$, carbon emissions will decrease if $r_E < -r_{CI}$. This criterion can be used to determine the peak of carbon emissions based on the trend and magnitude of change of energy consumption and carbon intensity.

For energy consumption (E), we assume equal annual growth in the years from 2017 through 2030, thus its annual percentage change ($r_E(t)$) of E will decrease overtime. Similarly, for carbon intensity (CI), we assume the carbon intensity of the energy mix will be equally cut in the next 13 years, which means that its annual percentage change ($r_{CI}(t)$) of *CI* will increase over time. The logic behind the assumptions underlines that China's energy consumption will slow down and energy transition will accelerate in the future as technology evolves. To peak emissions by 2030, the growth rate of energy consumption must be smaller than the reduction rate of carbon intensity, i.e., r_E (2030) $\leq -$ r_{CI}(2030). Therefore, under these assumptions, the minimum requirement for a peak by 2030 is $\overline{r}_E = -\overline{r}_{CI}$.

In other words, if $r_E(2030) > -r_{CI}(2030)$, i.e., $\overline{r}_E > r_E(2030) > -r_{CI}(2030) > -\overline{r}_{CI}$, the emissions peak will not happen by 2030 (He, 2014).

And we use $\overline{r}_E$ to denote the annual growth rate of energy consumption, averaged over 13 years from 2018 to 2030 ($\overline{r}_E = \frac{\sum_{2018}^{2030} r_{E(t)}}{13}$). Similarly, $\overline{r}_{CI}$denotes the 13-year average of the increase rate of carbon intensity ($\overline{r}_{CI} = \frac{\sum_{2018}^{2030} r_{CI(t)}}{13}$). The $\overline{r}_E = -\overline{r}_{CI}$is hence named the Peaking Possibility Curve (PPC) (shown in Fig. 3). $\overline{r}_E$ is a non-linear function of the energy consumption target and $\overline{r}_{CI}$ is also a non-linear function of the non-fossil share of energy target.

2.4. Carbon emissions data

Emissions from fossil fuel consumption are used to represent the total carbon emissions because they constitute the large majority (80%) of China's total greenhouse gas emissions (Elzen et al., 2016).

We use the estimation of carbon emissions from Qi (2017) for consistency. We estimate China's carbon emissions based on the same methodology in 2006 IPCC Guidelines for National Greenhouse Gas. We include only energy-related carbon emissions. The calculation of historical carbon emissions is a top-down approach, which includes energy consumption, calorific value and carbon content per unit fossil fuels, and the average oxidation rate of the main equipment, carbon sequestration of fossil fuels for non-energy use. The formula for calculating carbon emissions from fuel combustion is: carbon emissions= (fuel consumption $\times$ carbon content per unit of calorific value fuel − carbon sequestration per unit of calorific value fuel) $\times$ carbon oxidation rate during fuel combustion.

Carbon sequestration rate refers to the ratio of carbon fixed to fossil fuels in their use as non-energy sources. Since these carbons are not being released into the atmosphere, it needs to be deducted from calculation of carbon emissions. Despite that the emissions data vary by sources (Guan et al., 2012; Korsbakken et al., 2016; Liu et al., 2015), the analysis and conclusion hold true across them. The comparison of different sources is presented in Table A1 in the Appendix.

3. Kaya Inequality and the conditions for emissions peak

As mentioned in Section 2, to peak emissions by 2030, the growth rate of energy consumption must be smaller than the reduction rate of carbon intensity, i.e. $\overline{r}_{\mathrm{E}} < -\overline{r}_{\mathrm{CI}}$. While the Kaya Identity describes the static relationship between carbon emissions and the driving factors, the Kaya Inequality provides a criterion for determining the time and condition of peak emissions based on the trends in those factors.

To apply this criterion, one needs to calculate r_E and r_{CI} for each point in time under different policy scenarios (i.e., a combination of 2030 policy targets of energy consumption and non-fossil energy share).

For energy consumption, China's National Energy Strategy set the energy consumption target at 6 Gtce (1 Gtce = 29.3×10^{12} MJ) by 2030 (NDRC, 2016). China's total energy consumption was 4.486 Gtce in 2017, leaving a room for growth of 1.514 Gtce over the 13 years from 2018 to 2030. Recent studies and current trends in economic restructuring (towards less energy-intensive sectors), along with energy efficiency improvements, suggest that national energy consumption is unlikely to exceed 5.5 Gtce by 2030 (Du, 2017; He, 2014; Li, 2014; Sheehan et al., 2014). Thus, we chose 6 and 5.5 Gtce as the upper and lower targets for energy consumption in 2030. The corresponding annual average growth rates $\overline{r}_E$ from 2018 to 2030 would be 1.6% and 2.3% respectively.

For non-fossil energy share, the decreasing level of carbon intensity reflects the increasing share of non-fossil energy in the overall energy mix. The share in 2017 was 13.8%, and the corresponding carbon intensity was 1.96 tCO_2 $(tce)^{-1}$. The *National Energy Strategy* set two targets for non-fossil energy share by 2030. The basic policy target is 20%, aligned with the NDC under the Paris Agreement, with the corresponding carbon intensity being 1.72 tCO_2 $(tce)^{-1}$. The other is an accelerated transition to generate 50% of electricity from non-fossil energy sources (NDRC, 2016), which would lead to a 25% share of non-fossil energy in primary energy consumption, assuming electricity use represents 50% of total energy by 2030. The carbon intensity would be 1.60 tCO_2 $(tce)^{-1}$ under this strengthened target. In the period of 2018−2030, $\overline{r}_{CI}$ equals 1.0% for the basic policy target of 20% non-fossil in primary energy, and 1.7% for the strengthened policy target of 50% non-fossil for electricity generation, or 25% non-fossil in primary. The accelerated low-carbon energy transition would be two to four times faster than that of 2005−2017. With the increasing rate of reduction of carbon intensity, the annual reduction rate is unlikely to be lower than 1.5% (He, 2014). In other words, the strengthened policy target for China's energy transition is plausible in the coming years.

Therefore, in this study, we have assumed several possible scenarios of energy consumption in 2030 and non-fossil energy share in 2030, from which we have given three policy scenarios: 1) he basic policy scenario represents 6.0 Gtce of energy consumption and 20% share of non-fossil energy by 2030, 2) the strengthened policy scenario represents 5.5 Gtce of energy consumption and 25% share of non-fossil energy by 2030, and 3) the climate aspiration scenarios represent 5.0 Gtce of energy consumption and 30% share of non-fossil energy by 2030 (Climate aspiration 1) or 5.5 Gtce of energy consumption and 35% share of non-fossil energy by 2030 (Climate aspiration 2).

To facilitate the comparison and contrast of policy scenarios, we develop a model to predict whether the policy scenario could bring a carbon peak by 2030 based on the Kaya Inequality as shown in Figs. 1–3. The use of the model is made simple: for possible combinations of policy targets for energy consumption and non-fossil fuel share, one can find the corresponding point in Fig. 3, either below, on, or above the PPC. If it is one of the latter two, the policy scenario would bring a carbon peak by 2030. In addition, the greater the distance from the point to the PPC the earlier the peak will appear, and the faster the pace of reduction.

A 5.5 Gtce energy consumption by 2030 could happen with different combinations of economic growth rates and energy efficiency improvements. Under different economic growth scenarios, the annual average efficiency improvement for containing energy consumption below 5.5 Gtce will range from 3.77% to 4.34%, which fall within the range of efficiency improvement since 2012. This also means a total of 39%–44% reduction from its 2017 level in 2018–2030, close to that of 2005–2017 (40%). Given the fact that energy consumption per GDP of the service and finance industries is only a quarter of that from construction and manufacturing, every percentage shift in economics structure will return a 2% change in efficiency. This indicates that economic restructuring alone can contribute a 1.5%–2% efficiency improvement every year.

4. Scenarios of a policy-driven emissions peak

Domestic energy policy is essential to delivering the international commitment made under the Paris Agreement. Considering its credibility in policy implementation and

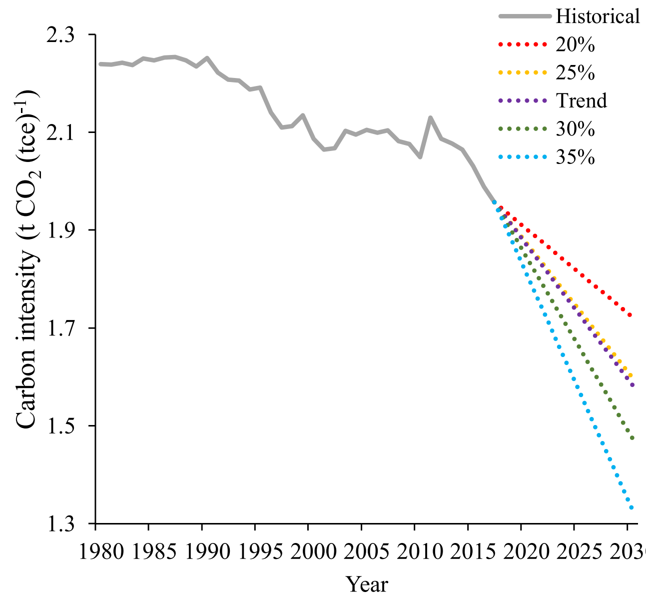

Fig. 2. Carbon intensity in China (1980–2030). The historical line represented the carbon intensity for 1980–2017, the red, yellow, green, blue, and purple represented the predicted annual carbon intensity in different scenarios (20%, 25%, 30%, 35% non-fossil in primary energy in 2030, and current trend in 2013–2017). We could see that the current trend extrapolation in energy transition matches the projection under the strengthened policy scenario.

target-setting, we estimate China's carbon emissions peak and reduction based on the national policy targets for energy consumption and its share of non-fossil energy.

Combinations of the basic and strengthened policy targets described above form four possible scenarios, resulting in the year of emissions peak falling between 2014 and 2052, at a level between 8.79 and 11.35 $GtCO_2$ (Table 1). Clearly, the basic policy scenario (or NDC scenario) of 20% non-fossil share of energy would be insufficient to deliver a carbon emissions peak by around 2030, and would have to be exceeded. If the strengthened policy scenario for energy transition is achieved with a non-fossil share of 25%, China's carbon emissions would peak in 2024 or 2033, respectively, depending on whether the total energy consumption is controlled under 5.5 or 6.0 Gtce. Clearly, accelerated decarbonization is key to delivering the emissions peak target under the Paris Agreement. Under the climate aspiration scenarios, by 2030, total national energy consumption would be 5.0 Gtce with 30% non-fossil energy (Climate aspiration 1 in Fig. 3), or a combination of 5.5 Gtce and 35% (Climate aspiration 2 in Fig. 3).

Fig. 4 compares emissions trajectories under three policy scenarios. The top branch of the curve represents the basic policy scenario, with 6.0 Gtce of energy consumption and 20% share of non-fossil energy by 2030. The point that represents basic policy scenario is far below the PPC in Fig. 3, and thus no peak would appear by 2030, failing to meet China's NDC target. The middle branch incorporates the strengthened policy target of 50% non-fossil for electricity, or 25% non-fossil in primary energy, with anticipated energy consumption of 5.5 Gtce by 2030. Since the point that represents strengthened

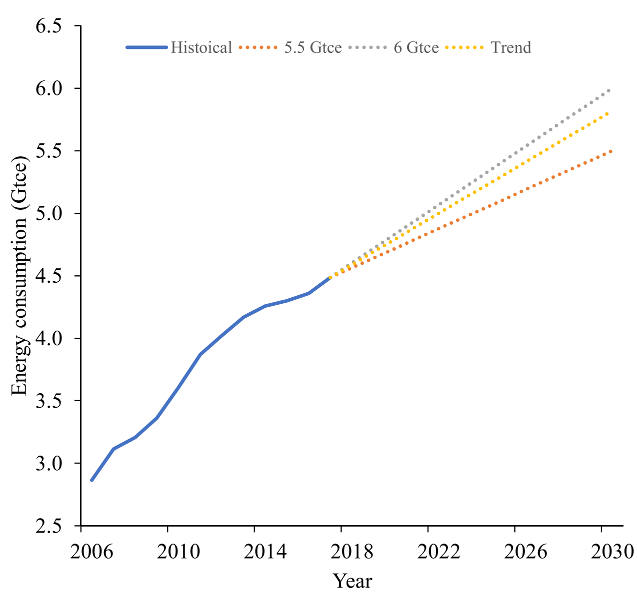

Fig. 1. Energy consumption in China (2006–2030). The historical line represented the energy consumption from 2006 to 2017, the red, yellow and grey represented the predicted annual energy consumption in different scenarios (5.5 Gtce energy consumption in 2030, 6.0 Gtce energy consumption in 2030 and current trend in 2013–2017).

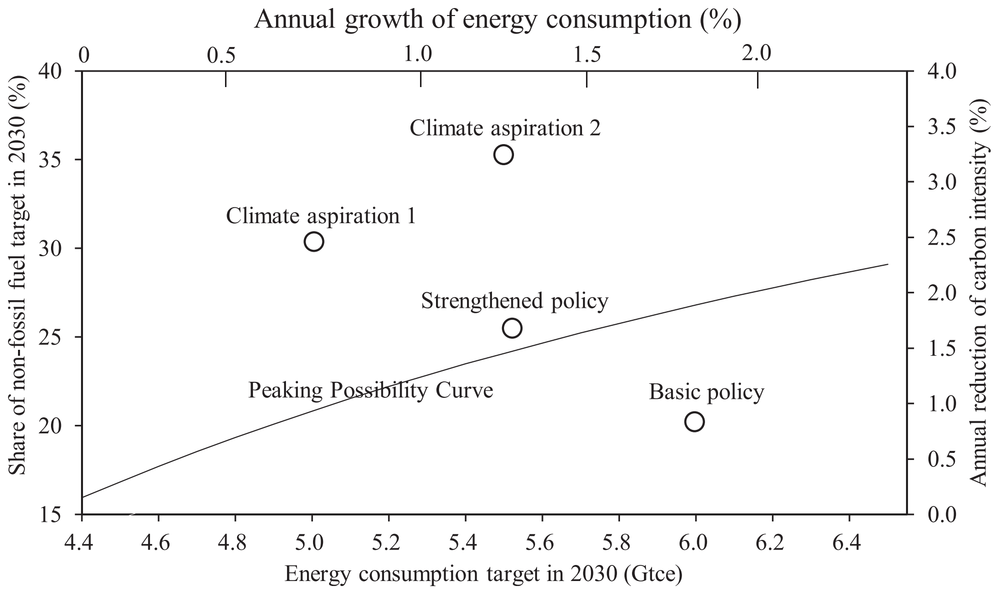

Fig. 3. Policy targets and emissions scenarios in 2030. The top *x*-axis represents the annual growth rate of energy consumption, averaged 2018−2030 ($\overline{r}_E$), as a non-linear function of the energy consumption target; and the right *y*-axis is the 13-year average of the decrease rate of carbon intensity ($\overline{r}_{CI}$), also as a non-linear function of the non-fossil share of energy target. The Peaking Possibility Curve $\overline{r}_E = -\overline{r}_{CI}$illustrates the minimum requirements of policy targets that deliver an emissions peak by 2030. $\overline{r}_{CI} = \overline{r}_E$ represents a curve that divides the domain into upper and lower parts. Each point above and on the curve represents a policy scenario that delivers peak carbon emissions by 2030. All combinations below the curve would fail to deliver a peak by 2030 (see Section 2). The dots, basic policy scenario, strengthened policy scenario and the two climate aspiration scenarios illustrate the four policy scenarios discussed in Section 3.

policy scenario is above the PPC in Fig. 4, this scenario would allow an emissions peak to appear in 2024, exceeding China's commitment under the Paris Agreement and meeting the necessary condition for the 2°C target. In fact, this scenario is consistent with the projection generated from trends in energy consumption and carbon intensity from 2013 through 2017. Our simulation shows that the 2024 peak emissions under strengthened policy scenario is only 0.1% higher than the 2017 level, indicating that the current plateau essentially represents peak emissions, which would enter a phase of steady decline by around 2025. Under strengthened policy scenario, the plateau would last for about a decade from 2014 to 2024. The third branch in Fig. 4 best represents the climate aspiration scenarios, indicating that China's emissions level had already peaked in 2014. With prohibitive costs, the climate aspiration scenarios would reduce carbon emissions back to the 2010 level by 2030, enough to meet China's obligation under the 2 °C scenario (Jiang et al., 2013).

Considering economic and technological feasibility, a stepwise acceleration of decarbonization may be possible through ambitious target-setting in China's Five-Year-Plans (Qi and Wu, 2013; Young et al., 2015). In devising the 14th FYP, China should consider a path towards 60% electricity use in total energy consumption, yielding 30% from non-fossil energy by 2030, and then seek a 35% target for the 15th FYP (Mccollum et al., 2016), building upon previous success. Historically, China's FYP performance in emission reductions has correlated with international climate efforts (Fig. 4); the rate of growth in emissions decelerated for three years after COP15 in Copenhagen and plateaued around the time of COP21 in Paris (Fig. 4).

Table 1
Peak year and peak emissions level (Gt) under different policy scenarios.

Energy consumption in 2030 (Gtce)	Peak year (peak emissions level (Gt))	
	Basic policy (non-fossil fuel share of 20% in 2030)	Strengthened policy (non-fossil fuel share of 25% in 2030)
5.5	2042 (9.68)	2024 (8.74)
6.0	2052 (11.35)	2033 (9.62)

The trends since 2012 strongly suggest that China's carbon emissions have reached a rather stable plateau with minor fluctuations, in effect indicating near-zero growth. Within the decade-long plateau, occasional fluctuations can be expected without undermining the essential conclusion about the long-term emissions trajectory. The plateau itself may be more meaningful than any specific year of peak.

In summary, to achieve the early peak of China's carbon emissions by 2030, the total energy consumption should be controlled below 5.5 Gtce and the proportion of non-fossil energy in the energy mix should be more than 25%. The better both targets are achieved, the earlier emissions will peak. Although the path to an earlier peak could be feasible, two major obstacles and uncertainty lie ahead. First, containing energy consumption within 5.5 Gtce may prove difficult. Despite considerable potential for energy efficiency improvement in manufacturing and heavy industry, as downward pressure on the economy increases from external or secular trends, local governments and state-owned enterprises may expand investment in energy-intensive industries and infrastructure projects to ensure a relatively high rate of GDP growth, resulting in a rapid growth of energy consumption.

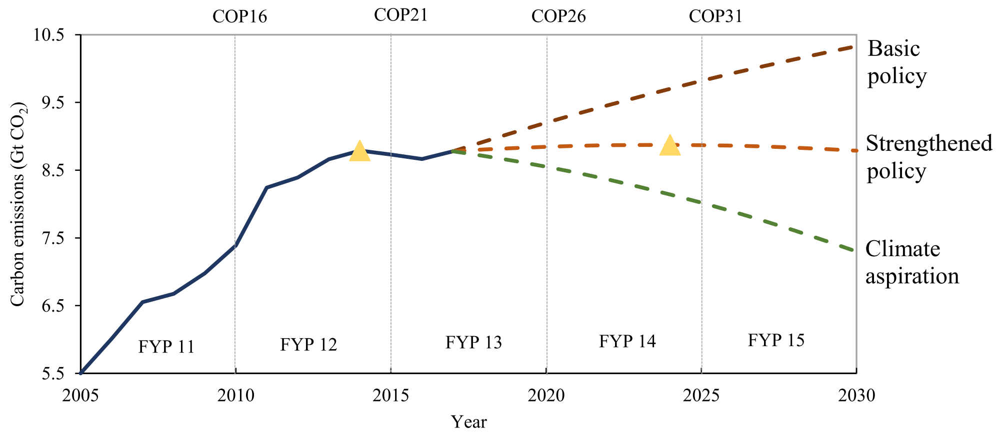

Fig. 4. Historical and projected emissions trajectories (2005−2030) under different policy scenarios (The triangle in the figure represents the peak years, FYP illustrates the Five-Year Plan). The brown line, the red line and green line represent the predicted annual carbon emission under basic policy scenario, strengthened policy scenario and climate aspiration scenario.

Second, the greater penetration of clean energy may invite challenges from the purveyors of the incumbent energy source (i.e., those that are emissions-intensive), slowing down its development. In the recent wave of infrastructure investment, restrictions on coal facility construction have been lifted. Many coal-fired power projects have been granted permission in the name of matching generation for Ultra-high-voltage (UHV) transmission lines. If the development of non-fossil energy in China falls behind expectation by 100 GW by 2030, the country's trajectory will return to the basic policy scenario, corresponding to an increase in coal consumption by about 0.2 Gtce and carbon emissions by about 0.4 Gt CO_2, making it difficult to achieve an early emissions peak.

5. Conclusion and implications for global climate actions

We found that controlling carbon intensity of the energy system, or the non-fossil share of energy, is critical to achieving carbon peak in China. Our results show that a mere 20% of non-fossil in the overall energy mix could not lead to a carbon peak around 2030. To achieve the peaking target for the Paris commitment, China would have to increase the non-fossil share of the energy system. Fortunately, the current projection of the future energy mix supports a much greater share of non-fossil energy in the national system. If this trend sustains, the current plateau of carbon emissions would eventually lead to a declining point before 2030, fulfilling China's NDC commitment for peaking time. To achieve the early peak of China's carbon emissions by 2030, the total energy consumption should be controlled below 5.5 Gtce and the proportion of non-fossil energy in the energy mix should be more than 25%. In devising the 14th FYP, China should consider a path towards 60% electricity use in total energy consumption, yielding 30% from non-fossil energy by 2030, and then seek a 35% target for the 15th FYP, building upon stable plateau of carbon emissions.

The encouraging trends of carbon emissions are largely driven by economic deceleration and slower growth in power demand (Gong et al., 2016; Liu et al., 2015; OECD, 2015). This economic New Normal, together with a structural shift to sectors with lower energy intensity and an overall priority for quality growth, enables faster substitution of coal-fired power generation by non-fossil energy sources. Behind these changes is a major shift in the national development policy. China's modernization goals, advanced from 2050 to 2035, call for fundamental improvements of environmental quality, necessitating an energy revolution to slowdown the growth of energy consumption and to phase out fossil fuel use. These domestic policies seem to be working in synergy with global climate targets.

These developments in China have critical policy implications for the rest of the world. China's economic slowdown and restructuring make it possible for a more expeditious substitution of coal-fired power generation by renewable sources. The real game changers are the evolving energy technologies (Guan et al., 2014), market dynamics (Liu et al., 2015), and less energy-intensive consumer behaviors (Yu et al., 2018) that break the inertia of the present energy structure, making deep decarbonization possible. Finally, our findings confirm the conclusion of the UNEP Gap analysis that China is on track to not only deliver but to exceed its NDC. Considering the fact that some of the major developed economies may be falling behind in meeting their NDC pledges (Victor et al., 2017), China has become the clear leader in delivering on the Paris Agreement. Other countries should reassess and recalibrate their efforts to more effectively, and ambitiously, achieve the needed carbon emissions reductions to avoid dangerous global climate change (Meinshausen et al., 2015).

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2020.05.008.

References

Convery, F.J., Wagner, G., 2015. Reflections—managing uncertain climates: some guidance for policy makers and researchers. Rev. Environ. Econ. Pol. 9 (2), 304–320.

Du, X., 2017. Thoughts on national energy production and consumption revolution strategy. China Econ. Trade Herald 15, 44–45 (in Chinese).

Elzen, M.D., Höhne, N., 2010. Sharing the reduction effort to limit global warming to 2°C. Clim. Pol. 10 (3), 247–260.

Elzen, M.D., Fekete, H., Höhne, N., et al., 2016. Greenhouse gas emissions from current and enhanced policies of China until 2030: can emissions peak before 2030? Energy Pol. 89, 224–236.

Gong, W., Xu, Z., Wu, Q., 2016. Authoritative source on China's economy. The People's Daily, 9 May (in Chinese).

Goodwin, P., Katavouta, A., Roussenov, V.M., et al., 2018. Pathways to 1.5 °C and 2 °C warming based on observational and geological constraints. Nat. Geosci. 11 (2), 102–107.

Green, F., Stern, N., 2016. China's changing economy: implications for its carbon dioxide emissions. Clim. Pol. 17 (4), 423–442.

Guan, D., Liu, Z., Geng, Y., et al., 2012. The gigatonne gap in China's carbon dioxide inventories. Nat. Clim. Change 2 (9), 672–675.

Guan, D., Klasen, S., Hubacek, K., et al., 2014. Determinants of stagnating carbon intensity in China. Nat. Clim. Change 4 (11), 1017–1023.

He, J., 2014. Analysis of CO_2 emissions peak: China's objective and strategy. Chin. J. Popul. Resour. Environ. 12 (3), 189–198.

Jackson, R.B., Canadell, J.G., Le Quéré, C., et al., 2015. Reaching peak emissions. Nat. Clim. Change 6 (1), 7–10.

Jiang, K., He, C., Liu, J., 2016. Transition to a low-carbon future in China towards 2°C global target. In: Enabling Asia to Stabilise the Climate. Springer, Singapore, pp. 23–40.

Jiang, K., Zhuang, X., Miao, R., et al., 2013. China's role in attaining the global 2°C target. Clim. Pol. 13 (Suppl. 01), 55–69.

Kaya, Y., 1990. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. In: Presented at the IPCC Energy and Industry Subgroup. Response Strategies Working Group, Paris.

Kemp, L., 2017. Better out than in. Nat. Clim. Change 7 (7), 458–460.

Korsbakken, J.I., Peters, G.P., Andrew, R.M., 2016. Uncertainties around reductions in China's coal use and CO_2 emissions. Nat. Clim. Change 6 (7), 687–690.

Lewis, S.L., Maslin, M.A., 2015. Defining the anthropocene. Nature 519 (7542), 171–180.

Li, W., 2014. Study on China's future energy development strategy: to consturct a safe, green and efficient energy system. People's Dail. 28. November (in Chinese).

Liu, Q., Chen, Y., Teng, F., et al., 2017. Pathway and policy analysis to China's deep decarbonization. Chin. J. Popul. Resour. Environ. 27 (9), 162–170 (in Chinese).

Liu, Z., Guan, D., Wei, W., et al., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 524 (7565), 335–338.

Mccollum, D.L., Rogelj, J., Krey, V., et al., 2016. The Emissions Gap Report 2016: a UNEP Synthesis Report. https://www.unenvironment.org/resources/emissions-gap-report-2016. (Accessed 26 November 2016).

Meinshausen, M., Jeffery, L., Guetschow, J., et al., 2015. National post-2020 greenhouse gas targets and diversity-aware leadership. Nat. Clim. Change 5 (12), 1098–1106.

Millar, R.J., Fuglestvedt, J.S., Friedlingstein, P., et al., 2017. Emission budgets and pathways consistent with limiting warming to 1.5 °C. Nat. Geosci. 10 (10), 741–747.

NDRC, 2016. National Strategy on Energy Production and Consumption Revolution (2016-2030). http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201705/W020170517397451808076.pdf (in Chinese).

OECD, 2015. Economic outlook No. 95: long-term baseline projections. http://stats.oecd.org/viewhtml.aspx?datasetcode=EO95_LTB&lang=en.

Peters, G.P., Andrew, R.M., Solomon, S., et al., 2015. Measuring a fair and ambitious climate agreement using cumulative emissions. Environ. Res. Lett. 10 (10) https://doi.org/10.1088/1748-9326/10/10/105004.

Peters, G.P., Andrew, R.M., Canadell, J.G., et al., 2017. Key indicators to track current progress and future ambition of the Paris Agreement. Nat. Clim. Change 7 (2), 118–122.

Qi, Y., 2017. Annual Review of Low-Carbon Development in China (2017). Social Sciences Academic Press, Beijing (in Chinese).

Qi, Y., Wu, T., 2013. The politics of climate change in China. Wiley Interdiscipl. Rev. Clim. Change 4 (4), 301–313.

Qi, Y., Lu, J., 2018. China's Coal Consumption Has Peaked. http://africa.chinadaily.com.cn/weekly/2018-01/19/content_35538975.htm. (Accessed 19 January 2018).

Qi, Y., Wu, T., He, J., et al., 2013. China's carbon conundrum. Nat. Geosci. 6 (7), 507–509.

Qi, Y., Stern, N., Wu, T., et al., 2016. China's post-coal growth. Nat. Geosci. 9 (8), 564–566.

Rogelj, J., Den, E.M., Höhne, N., et al., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534 (7609), 631–639.

Sheehan, P., Cheng, E., English, A., et al., 2014. China's response to the air pollution shock. Nat. Clim. Change 4 (5), 306–309.

Stern, N., 2007. The Economics of Climate Change: the Stern Review. Cambridge University Press, Cambridge.

Stern, N., 2015. Economic development, climate and values: making policy. Proc. Biol. Sci. 282 (1812) https://doi.org/10.1098/rspb.2015.0820.

Victor, D.G., Akimoto, K., Kaya, Y., et al., 2017. Prove Paris was more than paper promises. Nature 548 (7665), 25.

Young, O.R., Guttman, D., Qi, Y., et al., 2015. Institutionalized governance processes: comparing environmental problem solving in China and the United States. Global Environ. Change Hum. Pol. Dimens. 31, 163–173.

Yu, B., Wei, Y., Kei, G., et al., 2018. Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households. Nat. Energy 3 (2), 109–118.