Projection of energy mix in China using carbon emission pinch analysis

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Abstract. This work uses carbon emission pinch analysis (CEPA) method to analyze the energy mix of power generation in the Chinese power sector. It proposes to explore the optimal energy mix to achieve effective control of carbon emissions while meeting electricity demand. Under the constraint of global carbon neutrality, China's power industry is reducing carbon emissions by transforming the energy mix. The energy mix of China's power industry in 2030 and 2050 is analyzed according to the policy requirements and the emission reduction effect of the optimal combination. The study shows that vigorously reducing coal power, developing wind power and solar power as the main renewable energy sources, and vigorously developing the renovation and new construction of carbon capture and storage (CCS) technology for coal power are more conducive to reducing carbon emissions. The goals are up to achieve 4073.13 Mt CO₂-e in 2030 and 3948.54 Mt CO₂-e in 2050.

1. Introduction
From 2012 to 2020, China's energy mix remained largely unchanged, but total consumption increased from 106.01 EJ to 119.42 EJ [1]. In 2019, coal accounted for about 56.8% of the energy mix, only slightly below the 2012 level (66.6%), while the share of renewables in the energy mix increased from 9.4% to 15.3 over the same period [2]. Therefore, it will be a challenge for China to achieve carbon peaking by 2030. China reportedly generated a total of 5,799.05 TWh of electricity in 2015, the vast majority of which, 4,264.02 TWh (73.53%), came from fossil fuels (mainly coal). Nuclear power generation is 136.69 TWh (2.36%) and the rest (22.11%) comes from renewable energy sources such as solar, wind energy and Hydropower [3]. In comparison, about 67.4% of the United States electricity in 2015 came from fossil fuels, including coal (50.97%), natural gas (47.69%) and oil (1.34%). Nuclear and renewable energy account for 19.38% and 7.43% of the energy mix, respectively [4].

General Secretary Xi Jinping proposed at the 3rd Paris Peace Forum that China will increase its national autonomous contribution and strive to peak carbon dioxide emissions by 2030 and reach carbon neutrality by 2060, and that China intends to develop an implementation plan for this purpose. This paper uses CEPA method to explore the optimal energy mix for achieving sustainable development and effective control of carbon emissions while meeting electricity demand.
2. Methodology

2.1. Carbon emission pinch analysis (CEPA)

The CPPA method is a structural approach to electricity generation planning that takes into account carbon emission limits. Tan and Foo developed the CEPA technique and introduced for the first time a diagram called the energy planning pinch point diagram (EPPD). They use the methodology to illustrate how a country or region can achieve a predetermined emissions target by introducing zero-carbon energy [5]. The EPPD was later extended to scenarios where the planning objectives are met by increasing low carbon energy [6]. Matteo et al. used CEPA in the UK power generation sector and they found that CCS technology can significantly reduce carbon emissions and mitigate the greenhouse effect, while achieving negative emission technologies is equally important [7]. Also, the technique has been applied by various countries, including those in the European Union [8], Ireland [9], and Arabia [10] for climate-energy-water relationship studies in the power generation sector, Poland [11], and China [12] for multidimensional pinch point analysis for sustainable development planning in the power sector. The energy planning pinch point diagram is an important graphical representation tool of CEPA technology, which deals with how to obtain the minimum demand for energy to meet the region's energy needs under the carbon constraint.

The specific steps for drawing the pinch point diagram are summarized as follows [13]:

- Ranking of carbon emission factors from highest to lowest for all forms of electricity generation.
- All generation methods will be plotted on the load-energy diagram (with energy sources as horizontal coordinates and CO2 emissions as vertical coordinates) in ascending order of their carbon emission factors, forming a composite energy supply curve.
- Because energy supply has to meet energy demand, when the energy supply curve is to the left of or above (any part of) the demand curve, then a clip point diagram is not feasible. This requires shifting the energy supply curve to the right (zero carbon energy) or at a certain slope (low carbon energy) until the energy demand curve is completely to the left of the energy supply curve, and the intersection point formed by the two, which is the pinch point.
- Energy supply curves other than the energy corresponding to the end of the energy demand curve are excess energy and that part of the energy supply can be eliminated. Emissions between the energy supply curve and the energy demand curve on the vertical line at the end of the energy demand curve is the cuttable carbon emissions.

3. Case Study

3.1. Scenario selection and data sources

We select policy scenarios for detailed analysis. The electricity demand is projected to be 10,000 TWh in 2030 and 13374 TWh in 2050 [14]. In addition, China wants to reach a double carbon plan in the future, which means carbon emissions of less than 4073.13 Mt CO2-eq in 2030 and less than 3948.54 Mt CO2-eq in 2050, provided that electricity generation capacity is met.

At present, the main types of power generation are coal, natural gas, solar, nuclear, hydroelectric, wind and other renewable energy sources. Achieving a transformation in the energy mix of the power industry is an important way to cut carbon emissions at present. People want to get rid of their dependence on fossil energy as soon as possible, make fuel switching, accelerate the development of renewable energy-based power generation technologies, increase investment in wind, solar, hydropower and nuclear, and achieve rapid reductions in carbon emissions through the use of technologies such as CCS. Table 1 shows the emission factors for the various energy sources. These carbon emission factors are a condition for drawing the country's comprehensive energy curve.

3.2. Analysis of Carbon Emissions in China, 1995-2015

Based on China's carbon emissions and electricity generation data for 1995, 2000, 2005, 2010, and 2015, Figure 1 shows the carbon footprint of China's electricity generation portfolio from 1995-2015 and the
The carbon intensity of China's emissions for these five years.

Table 1. Emission factors for various energy sources

| Power generation method     | Carbon emission factor (kt CO₂-e/GWh) | References |
|-----------------------------|--------------------------------------|------------|
| Coal                        | 0.990                                | (Lau et al., 2014) |
| Coal (CCS)                  | 0.602                                | (Lau et al., 2014) |
| Oil                         | 0.700                                | (Lau et al., 2014) |
| Natural Gas                 | 0.611                                | (Lau et al., 2014) |
| Other Renewable Energy      | 0.527                                | (Lau et al., 2014) |
| Nuclear Energy              | 0.026                                | (Lau et al., 2014) |
| Hydropower                  | 0.013                                | (Lau et al., 2014) |
| Wind Energy                 | 0.096                                | (Guo, 2011) |
| Solar                       | 0.292                                | (Guo, 2011) |

Figure 1. Carbon footprint of China's power generation portfolio, 1995-2015

There are similarities between the 1995 and 2015 generation portfolios. Coal is overwhelmingly dominant in the energy mix, with a total production of 744.477 TWh (73.9%) in 1995 and 4108.973 TWh (70.9%) in 2015. Renewable energy generation increased from 206.378 TWh in 1995 to 1535.028 TWh in 2015. As can be seen in Figure 1, carbon emissions from China's electricity generation sector were 780.21 Mt CO₂-eq in 1995, they increased sixfold to 4331.11 Mt CO₂-eq in 2015. The carbon emission factor in 2010 is higher than that in 1995, mainly because of the larger share of hydroelectric power generation in 1995 (i.e., 18.9%) compared to only 16.98% of total power generation in 2010. During the period from 2000 to 2015, the carbon emission factor decreased year by year due to the country's vigorous development of hydropower, such as the construction of the Three Gorges Dam. If thermal power plants vigorously develop the renovation and new construction of CCS technology for coal power, more CO₂ emission reduction can be achieved. In addition, the development of renewable energy sources, especially onshore and offshore wind and solar power generation to make up for the power gap.
3.3. China's carbon emission projections in 2030 and 2050

China's electricity demand is forecast to grow quickly, reaching 10,000 TWh by 2030 and 13,374.9 TWh by 2050. If the generation mix remains unchanged (i.e., maintaining the same energy mix as in 2015), the results for 2015, 2030, and 2050 will be the same as those shown in the generation mix pinch point diagram in Figure 2. As the energy mix remains unchanged and coal remains overwhelmingly dominant, total emissions in 2030 are twice as high as in 2015, and almost three times as high in 2050. On the basis of 2015, China is committed to reaching a double carbon target. Therefore, China needs to get rid of its dependence on fossil energy as soon as possible, carry out fuel switching, accelerate the development of renewable energy-based power generation technologies, increase investment in wind power, photovoltaic, hydropower and nuclear power, and achieve a rapid reduction in our carbon emissions through the use of technologies such as biomass and CCS.

According to the China Energy Vision 2030 projection, CO2 emissions strive to reach a peak in 2030. Coal will account for 45%; hydropower 17% of total electricity generation; nuclear 12%; wind energy 10%; and solar 5% [17]. As shown in Figure 3, meeting the 2030 carbon emissions target will require more coal-fired power plants to use CCS technology. In addition, the use of petroleum fuels with high carbon emission factors will have to be reduced. These gaps will therefore be filled by renewable energy generation with lower carbon emission factors.

According to the World and China Energy Outlook 2050, the energy structure will be three-legged: coal will account for 30.7%; natural gas will account for 16.5%; oil will account for 15.2%; and non-fossil energy will account for 37.8%. CCS technology gradually achieve large-scale commercial application, more than 85% of fossil energy generation equipment in 2050 to apply CCS technology [18]. Assuming that the 2050 emission reduction target remains at the 2030 level (4073 Mt CO2-eq). Then the energy mix should be adjusted to achieve this goal. Figure 4 shows the optimal electricity mix to meet the dual carbon target for China in 2030 and 2050. Comparing 2030 and 2050 in Figure 4, about 66% of the thermal power plants in 2030 are retrofitted with CCS technology. In 2050, this percentage reaches to 86.7%. For renewables, the share of renewables in the energy mix increases considerably compared to 16.2% in 2005, reaching 39.8% in 2030 and 42.1% in 2050. However, coal generation decreases from 81.7% in 2005 to 45% in 2030 and 34.8% in 2050. Thus, renewable energy substitution is a fundamental initiative to reduce carbon emissions in energy production.
Figure 3. Compound curve to meet electricity demand in 2030

Figure 4. Compound curve to meet electricity demand in 2030 and 2050

4. Conclusions
Environmental pressures from China’s growing electricity demand pose a major challenge to the power generation industry. According to CEPA, for China to achieve 193% electricity growth by 2050, while meeting its dual carbon target, the share of coal and oil in the energy mix would need to be reduced by 20.9% and the share of renewable energy generation in the energy mix would need to increase by 5.6%. Progressively exploit the key role of wind and solar renewable energy generation, while further reducing the carbon intensity of hydropower and biomass generation. In addition, CCS technology is the key technology to achieve carbon neutrality. Retrofitting coal power plants with CCS technology can achieve significant reductions in carbon emissions, and the rapid development of negative emission technologies, is a key technology for achieving carbon neutrality in the mid-21st century.
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