Coal transition in China

Options to move from coal cap to managed decline under an early emissions peaking scenario

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Executive Summary

An earlier emissions peak and decline is possible in China, with the right policies on coal

Coal is a dominant energy resource in China's energy mix for decades. Due to the increasing domestic environment concerns (e.g. air quality, water availability) and pressure to reduce greenhouse gas emissions, China is actively looking to phase out coal from its energy system. For instance, China's coal cap policy has already become a cornerstone of China's low carbon transition and the implementation of its target to ensure that its carbon emission peak by around 2030. The question is now how China can begin to prepare a managed decline of coal consumption.

Although the low-carbon transition is becoming a matter of political consensus in China, there are still various challenges that need to be carefully addressed. Those challenges include (but are not limited to):

- how market based instrument can be employed to replace traditional command and control approaches, so as to align market incentives and incentives for the clean energy transition;
- how to strengthen coordination between coal transition policy and other sectoral transition policies, especially with market reform policy in the electricity sector;
- how to phase out dispersed coal in the residential sector while ensuring that affordable alternative energy carriers to be provided to low income consumers; and
- how to compensate the coal transition process with just social policies to balance the various winners and losers.

This report argues that with carefully designed policy package, and with particular attention to transitioning awat from coal, China can successfully achieve the coal transition while the transition cost can be limited and managed where necessary. According to our analysis, recent macro-economic and technological developments, combined with additional policies to further limit coal use, could allow China to have its CO_2 emissions peak in year 2025 at 10.2Gt level and then drop down to 9.93Gt in 2030. Our analysis also suggests China's emissions could be 5.7Gt lower than 2020 by the end of 2050, with ambitious policies to tackle coal. This is lower than previous scenarios (**Figure ES.1**).

Phasing down coal use is essential to achieving the early peaking scenario

However, early peaking of CO_2 emissions calls for faster and effective deployment of alternatives for coal consumption, especially in the power sector. The key pillars for a low carbon transition in China are as follows:

- replacing old coal assets with a low carbon electricity system with high penetration of non-fossil fuels and possibly some implementation of CCUS on thermal power;

Figure ES.1. CO2 emissions under 2025 vs 2030 peaking scenarios

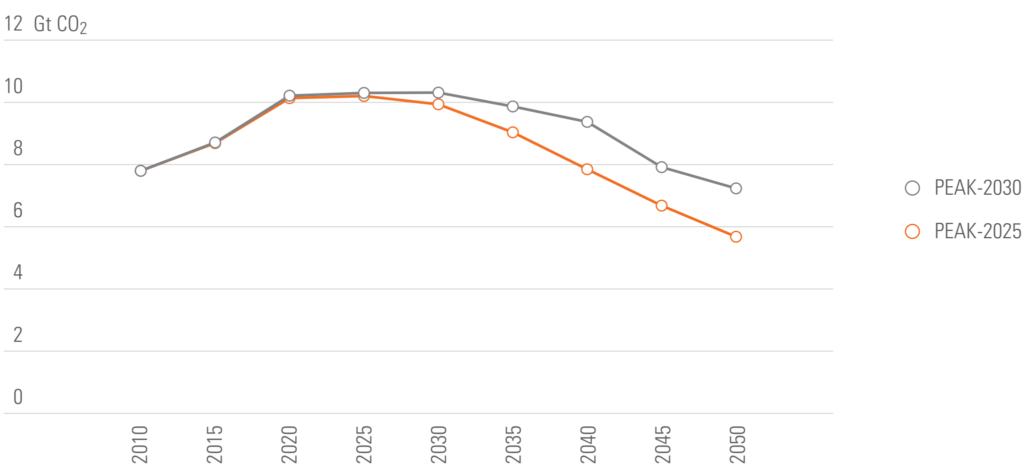
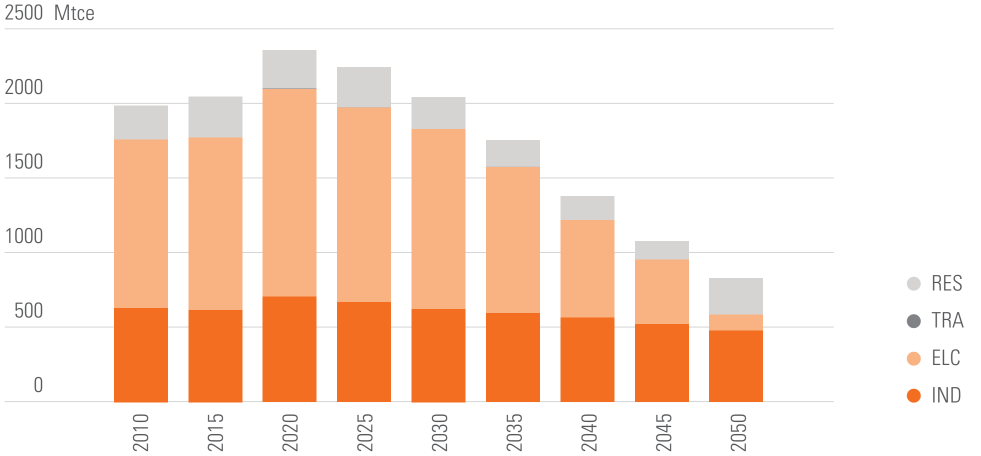


Figure ES.2. Coal consumption by sector under PEAK-2025 scenario



- enhanced decarbonisation in the industry sector through a combination of industry structure optimization, fuel switching, energy efficiency improvement;
- integrated coal phase out policies in building sectors with city planning polices targeted at controlling floor area, inhibiting the unnecessary early demolition of buildings, improving energy efficiencies of both buildings and appliances, and optimizing the energy mix.

With the implementation of those policies, China can achieve an early peaking of its energy-related carbon emission by around 2025, with a lower CO_2 emission level than originally anticipated, i.e. around 10 $GtCO_2$, and see its emissions begin declining thereafter.

Moving to an earlier peak and decline scenario implies a strong decline in especially thermal coal demand. As shown in **Figure ES.2**, coal demand would need to peak in 2020, followed by a steady reduction thereafter.

Feasible policy options exist for a managed coal transition in China

However, the coal transition in China will have some socio-economic aspects that will need to be anticipated and managed. These include changing the future value of coal related assets, declining demand coal from coal producing regions, and reducing the employment of coal sector workers, and ensuring cost-effective energy access during the transition from coal in the residential sector. Policy makers and sector stakeholders will thus need to explore solutions to these questions.

Several options exist. For example, for coal producing sectors, the labour policy aiming at low education workers is important to soften the social impact on low income workers. The central government would also need to provide transition funds to help local governments reestablish industries and avoid demographic decline.

For the electricity sector, a very large risk of stranded assets is approaching, with overcapacity much more likely than under-supply. The government should take immediate action stop building new coal power plants, accelerate the electricity reform and transaction of generation trade to identify least cost options to manage the stranded assets. Liberalising power market pricing in the electricity sector could also help to compensate for asset stranding and provide opportunities for coal plant to be retired or provide ancillary services to the power market instead of baseload power.

Finally, coal consumption in the buildings sector are closely linked with energy poverty and interacts with housing choice and infrastructure availability. In such cases, city planning policies together with infrastructure retrofit policy and subsidies for clean energy can contribute to shift away from coal in residential sectors.

At the same time, reducing coal use can also help China achieve other important policy priorities. For instance, the early phase out of thermal coal will also deliver important co-benefits, such asreducing methane emissions due to coal production, reducing health impacts due to poor air-quality and limiting stresses on water for plant cooling. Market liberalization in the power sector can help to reduce wasteful investment, provide cheaper power prices for consumers, while accelerating the shift to alternative, clean energy.

As the largest coal consuming country, China is on its way to phase out coal through concrete policy packages and by promoting a low carbon economy. This transition will not only frame China's energy trajectory but also the world's energy trajectory through altering the expectation of producer countries that sell into the Asia Pacific thermal coal market. This report aims to suggest concrete issues, options and pathways for China to follow in implementing its domestic coal transition.

Introduction

In contrast with many developed countries, coal has hitherto remained the dominant energy source in China and accounted for more than 70% of the total energy consumption for the past 20 years, and 64% in 2015. The coal consumption in China achieved 4 billion tons in 2015, which is about half of global coal consumption (IEA, 2017). About 52% of Chinese coal is consumed in the electricity generation sector, while this share is lower than most of the developed countries (NBSC, 2017). The large amount of coal consumption has caused serious concerns on various social and environmental issues, such as carbon emissions, aggravating local air pollution and other problems. China has submitted its INDC (NDRC, 2015) and committed to peak its carbon emission around 2030. Compared to 2005 level, the carbon emission per unit of GDP will be reduced by 60-65% in 2030. And the share of non-fossil fuel consumption in total primary energy consumption should rise to roughly 20% in 2030.

Besides of the carbon mitigation, air pollution in China became a major economic and social issue across the country, especially in Beijing-Tianjin-Hebei area and Yangtze River Delta. The coal combustion contributes 91.18% of total SO_2 emission, 68.56% of NOx emission, and 52.74% to the primary PM2.5 emissions in 2012. According to the study of World Health Organization, the air pollution accounts for more than one quarter of premature death and more than 23% of the health problems in China. The local air pollutant emissions are highly related to fossil fuel combustion, especially coal consumption in China. Actions of energy conservation to reduce carbon emissions also reduce co-emitted air pollutants like SO_2, NOx and PM2.5, bringing co-benefits for air quality and public health.

In light of these multiple challenges, China takes controlling and limiting coal use as a core policy goal necessary for low carbon development, and has taken a series of policies and measures in recent years. In 2014, the state council issued the National Energy Development Strategy Action Plan (2014-2020), and clearly stated that, by year 2020, the total annual coal consumption should be capped at 4.2 billion tons/yr, and among the primary energy consumption the share of coal should be below 62%. In the National Air Pollution Control Action Plan issued by Ministry of Environmental Protection, National Development and Reform Commission and other key ministries, the detailed coal consumption control target is further explicitly stated for key provinces and cities. The coal control in China is of high importance not only for carbon mitigation to achieve the peaking target, but also very critical for local pollutant reduction and air quality improvement.

Coal in the National Context

Role of coal in the national energy system

China is both the biggest coal consumer and coal producer in the world (Qi et al, 2016). In year 2015, China produced 3.7 billion tons of coal (including both steam coal and coking coal) and consumed 3.97 billion tons of coal, accounting for 47% of global production and around 50% of global consumption. The energy mix in China is also dominated by the coal with a share of 64% in primary energy, much higher than the world average of 28%. The four biggest coal consuming sectors are power generation, iron and steel industry, the construction material industry and the chemical industry. As a major coal producing country, the domestic coal production provide a sound basis for energy security. For a long time, the amount of imported coal is relative low. But after year 2008, the coal import has boomed with an unprecedented rate. In 2009, China import coal more than 100 million tons, and then become the largest importer in year 2011. The coal import exceeded 200 million tons and 300 million tons respectively in year 2012 and year 2013. Different with the fast growing import, the exports drops substantially in past decades.

Export volume has been increasing since the 1980s to the beginning of the 21st century, especially after the 1998 financial crisis. Export volume in 1980 was only 6.32 million tons, which reached 36.48 million tons in 1996, reached a peak of 93.88 million tons in 2003. Since then, exports have declined rapidly, dropping to 45.43 million tons in 2008 and reaching 7.51 million tons in 2013, which is 8% of exports in 2003.

Coal is the main raw material and fuel for industry sectors. The major reason for the explosive growth of imported coal is the rapid expansion of energy-consuming industries in coastal areas. The rapid expansion of production capacity and output of energy-consuming industries in coastal areas has prompted the rapid expansion of coal demand in thermal power, metallurgy, and building materials, etc.

The most imported coal is thermal coal, followed by coking coal, accounting for about 2/3 of overall imported coal, which is much higher than anthracite coal and other coals. This is consistent with the rapid expansion of the heavy chemical industry in coastal areas, and also the increased power generation capacity located in coastal areas due to the advantages of lower shipping cost.

The rapid changes in the coal import and export trade have effectively supported the socio-economic development of China's coastal areas and eased the contradiction between its energy supply and demand. However, it also shows that the social and economic development of China is increasingly dependent on imported coal, became an energy security concern for government. In the future, in line with strengthening energy conservation and emissions reduction, China will build a coal supply system that is mainly domestically supplied and supplemented by imports to ease the rapid growth of coal imports.

Coal is also the biggest source of air pollutants in China, accounting for 91% of SO_2, 69% of NOx and 52% of primary PM2.5 emissions. Coal consumption has grown very fast in past decades from 1.3 billion tons in year 2000 to 3.5 billion tons in year 2013, with an annual growth rate of 6.5% in the period 2000-2016. In 2014, for the first time coal consumption stopped growing and began to decrease by 3% (Qi et al, 2016). In year 2015 and 2016, the coal consumption was reduced further by 3.5% and 4.7% respectively (Han et al, 2016). For year 2017, the initial statistics from National Bureau of Statistics shows a slightly 0.4% increase compared with year 2016. But most of experts consider this increase as a short term effect due to the rebound of energy intensive industry.

The reduction of coal consumption in China is a combined effect of several factors. These include: the growth slowdown and restructuring of the economy, known as the "new normal"; efforts to pursue air quality; and actions on climate change (Tang et al, 2016)(Qi et al, 2016).

Air quality is a key driver in the process of coal transition in China. In the report on global burden of disease by World Health Organization, particulate matter in outdoor air quality ranked fourth in overall health burden risk factors of China (Sun et al, 2016). Coal related PM2.5 emissions are responsible for about 670 000 premature death in 2012, through chronic obstructive, lung cancer, stroke and ischemic heart disease (Yang and Teng, 2016). The production, transportation and consumption of coal in China also raises environment damage in other sectors, such as water scarcity, soil erosion, vegetation degradation and desertification. Those environment costs associated with coal are not fully reflected the coal pricing system of China and are framed as "hidden cost" of coal. According to a study of Tsinghua University, the real damage cost of China's coal production and consumption is about 260 yuan/ton of coal ($37.65/ton) (Yang and Teng, 2016). Although parts of China's pricing mechanism take these costs into consideration, the extent of environmental taxes is not enough to internalize external costs. China's current coal pricing mechanism only has 30-50 yuan/ton of coal in environmental taxes, mostly focused on the production side, with only 5 yuan/ton in coal pollution fees on the consumption side.

In 2014, the state council issued the National Energy Development Strategy Action Plan (2014-2020), and clearly stated that, by year 2020, the total annual coal consumption should be capped at 4.2 billion tons/yr, and among the primary energy consumption the share of coal should be below 62%. In the 13th Five Year Plan (2016-2020), China included for the first time a target of a national coal consumption cap of 4.1 billion tons for 2020, a more stringent target compared with 4.2 billion tons in year 2014. The environmental protection chapter of the 13th Five Year Plan adds a goal of reduce the primary energy share of coal to 58% by 2020, from the level of 64% in year 2015, also more stringent than targets set in year 2014. Recognizing that air quality is a regional issue, the Five Year Plan also establishes specific coal consumption reduction targets for specific regions, such as 10% for Jing-Jin-Ji region and Pearl River Delta, 5% for Yangtze Delta. If these regional targets can be fulfilled by year 2020, this will result to a reduction of 140 million tons in specific regions coal by 2020 compared with year 2015.

Current policy priorities and issues

Although the transition towards a low carbon economy has become a political consensus in China, some barriers and challenges still need to be overcome in the future. The most important one is how market based policy instruments can play a role in the transition. The Chinese Government used to adopt command and control regulation to allocate energy consumption, coal consumption and carbon emission intensity targets to local government then to enterprises (Wang et al, 2016). However this top-down approach has triggered problems of data cheating and efficiency loss. Pricing mechanism through tax or cap and trade is more preferable in the future. By developing reasonable environmental taxes on coal production and consumption, it is possible to internalize the external damage costs generated by coal production and consumption, use price mechanisms to efficiently adjust the production and consumption of coal, and achieve adjustment and optimization of the energy mix.

The second challenge is the coordination with other policy transition processes, especially the liberalization of power market (Yuan et al, 2016). The electricity price in China is still under heavy regulation and not open to competition. In past years, the coal price has decreased substantially due to the low demand, but the electricity price failed to adjust accordingly. The mismatch between coal price and electricity price has led to an unintended competiveness of coal based power plant and then an overinvestment in coal based generation capacity. The inconsistency between climate policy and policies of power sectors in China indicates that the current level of policy coordination is still low in developing countries. In order to achieve a positive synergy, domestic policy coordination is key to enhance policy coordination in key domains with a view to increase the probability of success.

The third challenge is the phase out of so-called “dispersed coal” in residential heating and cooking and small-industrial boilers without any end-of-pipe treatment. The GHG Control Work Plan and Environmental Protection Plan aim to replace those dispersed coal by natural gas and electric heating. Nonetheless, it should be noted that most of coal dependent family and companies are poor family and small scale business, they simply either do not have gas access or cannot afford gas and electric heating. A key policy challenge is therefore how to develop access to affordable alternative sources of heating energy for these applications.

Fourthly, the issue of social equity poses another challenge for the coal transition. Coal rich provinces who have built their revenue system on coal resources will have to face the problem of job loss in mining industry and related social and economic problems. The coal transition policy needs to be compensate by other policies, e.g. labor policy to facilitate the reemployment of mine workers, finance transfer policy to help transition in coal related industry and cities. The average education level of employees in coal enterprises is low. According to statistics, as of the end of 2010, among the employees in the coal industry. There are about 5 million employees in coal industries in China, among them there were 889,000 employees with level of college education or above, accounting for 16.87%, which was 16% lower than the national average level of the energy industry. The proportion of employees with doctoral, master, undergraduate, and college degrees is lower than the average of the energy sector by 0.13%, 1.03%, 8.13%, and 6.66%, respectively. Most of workers in coal sectors are off-farm workers who have very limited job choice and vulnerable to the policy consequence.

Analysis of alternative thermal coal transition scenarios for China

Quantitative Coal Scenarios

To reveal the potential role of coal transition in achieving the peaking goal of CO_2 emissions in 2030 proposed by China's INDC under the Paris Agreement, or possibly even more ambitious early peaking, this study builds the PEAK-2030 and PEAK-2025 scenarios to respectively represent pathways in accordance with different mitigation ambitions. In contrast to PEAK-2030, the PEAK-2025 scenario includes more stringent requirements on the new-entry/phase-out of coal-fired electricity generation units, and the elimination of excess production capacity in industry, especially in the cement, paper, iron and steel sectors. Furthermore, it also induces a much faster expansion of renewable energies utilization in power sector, and higher level of energy efficiency and electrification in transportation sectors, and the 'coal shift to gas' and 'coal shift to electricity' policies will be accelerated in residential heating sectors. It should also be noted that the 2050 vision target, the proportion that renewables account for in China's overall primary energy consumption surpasses 50%, can also be realized under PEAK-2025 scenario.

PEAK-2030 scenario

CO_2 emissions

China's INDC has declared specified timeline for CO_2 emission peaking (around 2030 or early) and concrete target for carbon intensity reduction (60-65% below the 2005 level by 2030), to which the coal transition could make significant contributions. As shown in **Figure 1**, the CO_2 emissions will peak in the year 2030 at 10.3Gt under PEAK-2030 scenario, approximately 32.6% higher than the base year (2010) level. Thereafter, the CO_2 emissions considerably decreases by 29.8% from the peaking level to 7.3Gt in the mid-century, around 7.0% lower than the base year.

Final energy consumption

The energy conservation measures have strong effects on restructuring the energy consumption mix, the representative characteristic of which is the decline in coal utilization. Under PEAK-2030 scenario, the coal (including both thermal coal and coking coal) consumed by final sectors will first increase continuously towards 2020 and peak at about 2.37 Gtce, and then decreases to 2.1 Gtce

Figure 1. CO_2 emissions under 2030 peaking scenario

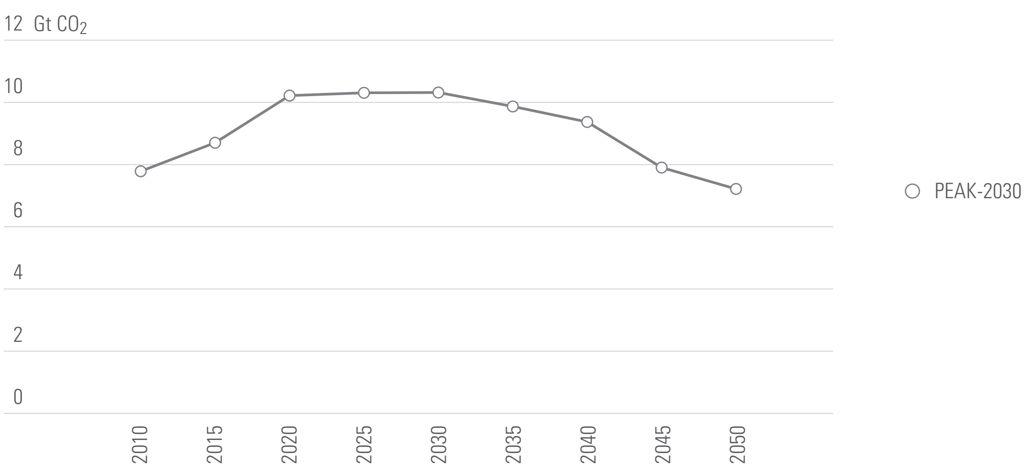
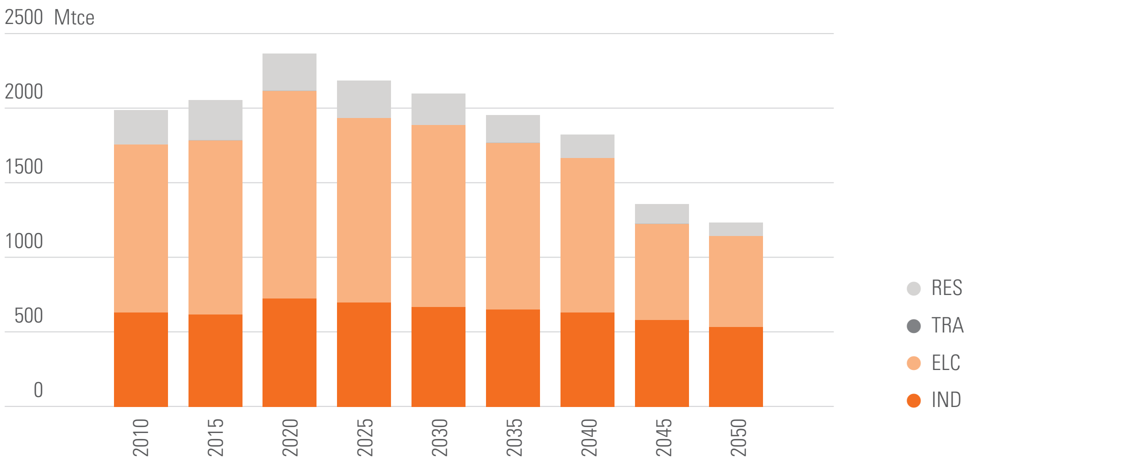


Figure 2. Coal consumption by sector under PEAK-2030 scenario



and 1.26 Gtce in 2030 and 2050, respectively. Among these coal-consuming sectors, electricity generation and industrial sectors remain the largest two coal consuming sectors, accounting for 58.7% and 30.7% in 2020, 57.9% and 32.0% in 2030, and 50.0% and 42.8% in 2050, respectively. While, coal consumption by residential sector considerably decline from 229.6 Mtce in the base year to 212.5 Mtce in 2030, and further down to 90.7 Mtce in 2050, with the associated contribution ratio dropping down from 11.5% to 10.1% and 7.2% in response, as presented in **Figure 2**.

Primary energy consumption

Under PEAK-2030 scenario, the primary energy consumption will first increase continuously towards 2030 and peak at about 5.69 Gtce, and then slightly decreases to 5.55 Gtce in the mid-century. Among all energy carriers, coal remains as the most significant contributor for almost the whole study period, and only after the year 2040 non-fossil fuels consumption together surpasses coal to become the largest driver. The amount of coal consumption increases from 2.59 Gtce in 2010 to peak at 3.03 Gtce in 2020, and then declines by 12.0% to 2.66 Gtce in 2030 and by 45.4% to 1.65 Gtce in 2050. The proportion that coal accounts for in overall primary energy consumption decreases throughout the whole study period, from 71.7% in the base year to 46.8% and 29.8% in 2030 and 2050, respectively. The development of non-fossil fuels should be noted, with an increasing share from less than 10% in 2010 to approximately 20% in 2030, and further up to 41.3% in 2050, as shown in **Figure 3**.

Figure 3. Primary energy consumption under PEAK-2030 scenario

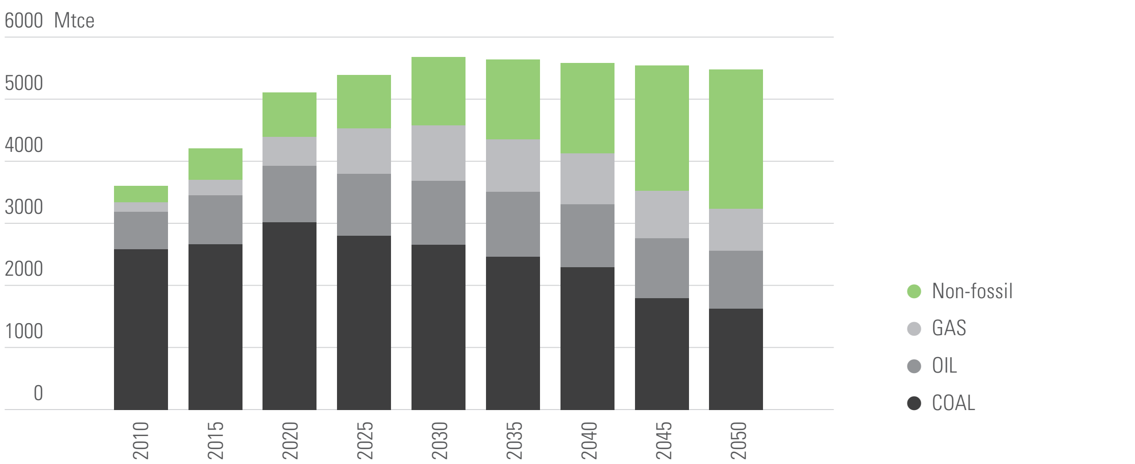


Figure 4. Electricity generation under PEAK-2030 scenario

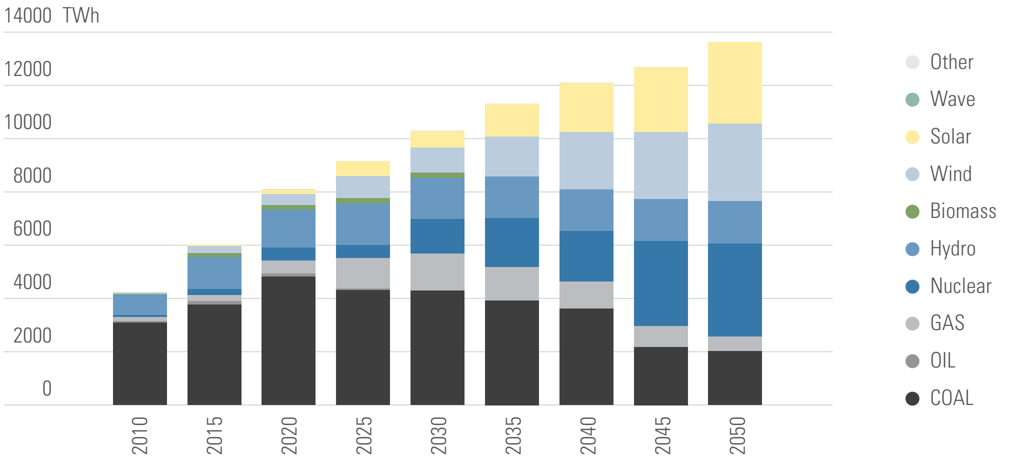
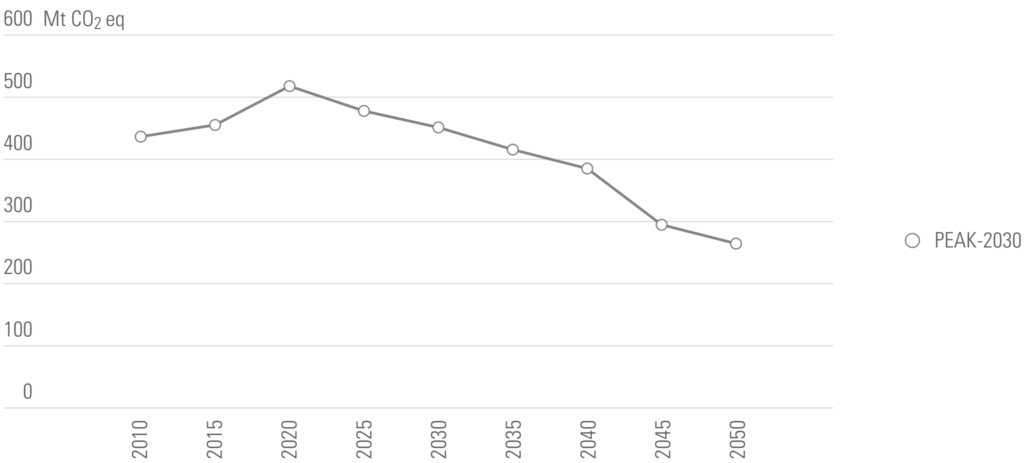


Figure 5. CH_4 emissions from coal mining under peaking scenarios



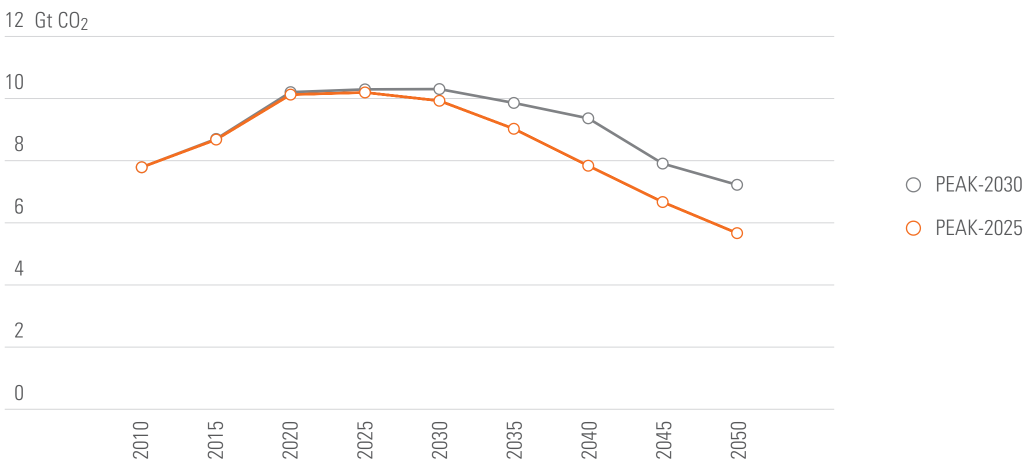
Electricity generation

Under PEAK-2030 scenario, the coal-fired electricity generation will peak around 2020 at 4818.9TWh, and then decline steadily to 4393.8TWh in 2030 and markedly 2100.6TWh in 2050. Accordingly, the proportion that coal-fired electricity generation accounts for in overall electricity generation decreases throughout the whole study period, from 73.3% in the base year to 41.8% and 15.0% in 2030 and 2050, respectively. Moreover, the electricity generated by non-fossil energy (including both nuclear and renewables) increases from 929.3TWh in 2010 to 4588.7TWh and 11397.0TWh in 2030 and 2050, respectively. The related proportion rises substantially from 22.0% in the base year to nearly 80% by the end of study period, as presented in **Figure 4**.

CH_4 emissions related to coal mining

Considering the fugitive CH_4 emissions associated with coal mining process, the coal transition and early peaking of CO_2 emission can also generate co-benefits of mitigating CH_4 emissions. As shown in **Figure 5**, the CH_4 emissions will peak in the year 2020 at 519.5MtCO_2e under PEAK-2030 scenario, approximately 18.6% higher than the base year level. Thereafter, the CH_4 emissions considerably decreases to 452.8 MtCO_2e and 268.2MtCO_2e in 2030 and 2050, respectively.

Figure 6. CO_2 emissions under 2025 vs 2030 peaking scenarios



PEAK-2025 scenario

CO_2 emissions

As shown in **Figure 6**, the PEAK-2025 scenario indicates a situation of early peaking in year 2025 at 10.2Gt level, then will drop down to 9.93Gt in 2030, nearly 0.4Gt lower than the PEAK-2030 scenario, and 5.7Gt by the end of 2050, about 1.6Gt lower than under the PEAK-2030 scenario.

Final energy consumption

Early peaking of CO_2 emissions calls for much faster and effective alternative for coal consumption, especially in power sector. Under PEAK-2025 scenario, the coal consumed by final sectors also peaks around 2020 at 2.35Gtce, slightly less than under the PEAK-2030 scenario. It will then decrease to 2.04Gtce and 796.8Mtce in 2030 and 2050, 3.1% and 36.6% respectively lower compared to the PEAK-2030 scenario. In comparison, the coal consumption in power sector will be 192.6Mtce in 2050, indicating a substantial decline of 434.7Mtce. Accordingly, the relevant fraction in overall coal consumption drops to 24.2%. Thereby, industrial sector becomes the most significant contributor of coal consumption, with a proportion of 30.8% and 60.5% respectively in 2030 and 2050, as depicted in **Figure 7**.

Primary energy consumption

Meanwhile as shown in **Figure 8**, the peaking level of primary energy consumption in 2030 under PEAK-2025 scenario is 5.46 Gtce, nearly 4.0% less than the PEAK-2030 scenario. The total amount will continuously decline and reach 5.00Gtce in 2050, which is 9.8% lower compared to the PEAK-2030 scenario. The amount of coal consumption will also peak in 2020 at 2.98Gtce, slightly less than under the PEAK-2030 scenario, while declines to 2.03Gtce and 1.09Gtce respectively in 2030 and 2050, approximately 135.2Mtce and 563.6Mtce lower than PEAK-2030 scenario. What's more, the proportion that coal consumption accounts for in total primary energy consumption under PEAK-2025 scenario is 46.3% and 21.8% in 2030 and 2050, compared to 46.8% and 29.8% respectively in the targeted years under PEAK-2030 scenario. Furthermore, the share of non-fossil fuels presents significant growth trend and climbs up to 50% in 2050, which can fulfill the 2050 vision target proposed by the National Development and Reform Committee.

Electricity generation

In contrast to PEAK-2030, the curb of coal-fired electricity generation under PEAK-2025 scenario is much more stringent, resulting in a substantial decrease down to 422.1TWh in the mid-century, as shown in **Figure 9**. Correspondingly, the proportion that coal-fired electricity generation accounts declines to 41.3% and 3.0% in 2030 and 2050, respectively. In order to fulfill the vision target of non-fossil fuels accounting for over 50% of overall primary energy consumption, the electricity generated by non-fossil energy carriers should be significantly expanded, reaching 13085.4TWh in 2050 and contributing for approximately 90% of total electricity generation.

Figure 7. Coal consumption by sector under PEAK-2025 scenario

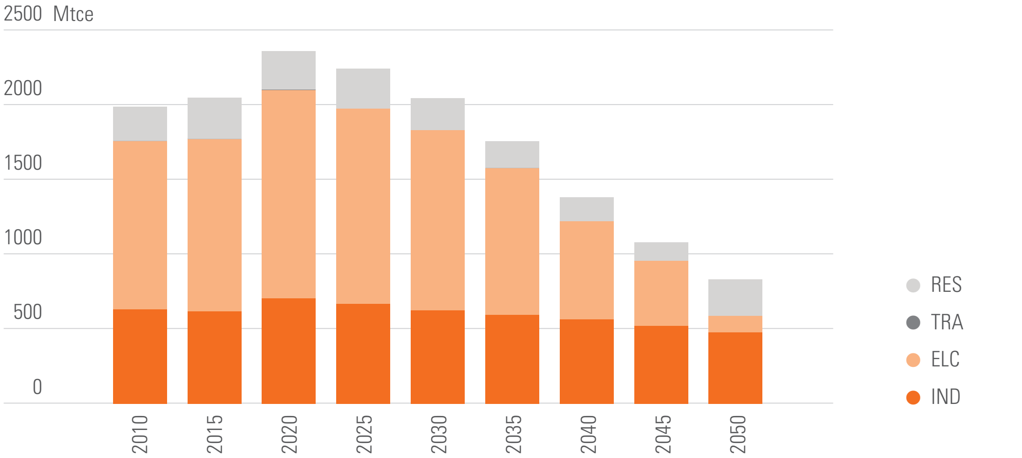
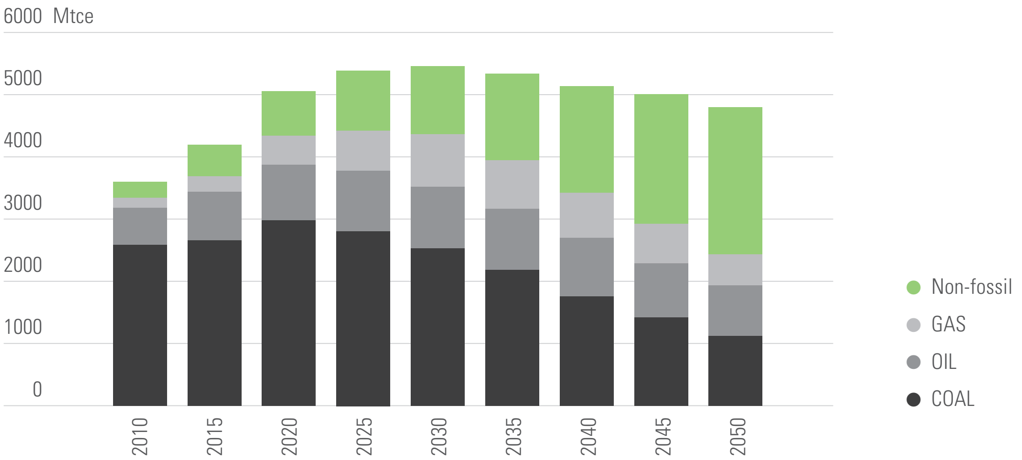


Figure 8. Primary energy consumption under PEAK-2025 scenario



CH_4 emissions related to coal mining

In contrast to the PEAK-2030 scenario, the fugitive CH_4 emissions associated with coal mining process will also peak in 2020 at 511.7MtCO_2e under PEAK-2025 scenario, thereafter the CH_4 emissions considerably decreases to 429.1MtCO_2e and 167.4MtCO_2e in 2030 and 2050, respectively. In comparison, the PEAK-2025 scenario indicates a marked co-benefits of CH_4 reduction of 23.7MtCO_2e and 100.9MtCO_2e for the year 2030 and 2050.

Coal-related policy options for moving to the earlier peaking scenario

It is of vital importance to look into the key sectors and recognize the major policy dimensions related to phasing out of coal accordingly. We will discuss the coal related policy dimensions from both sectoral and regional perspectives. On the sectors, we will focus on both production and consumption, for consumption we will discuss from a sectoral perspective including electricity, industry and buildings. While for key regions, we will mainly discuss the Jing-Jin-Ji region around Beijing.

For coal **production capacity**, due to the decline in coal demand and the large stock of new coal production capacity, it is also necessary to further increase

Figure 9. Electricity generation under PEAK-2025 scenario

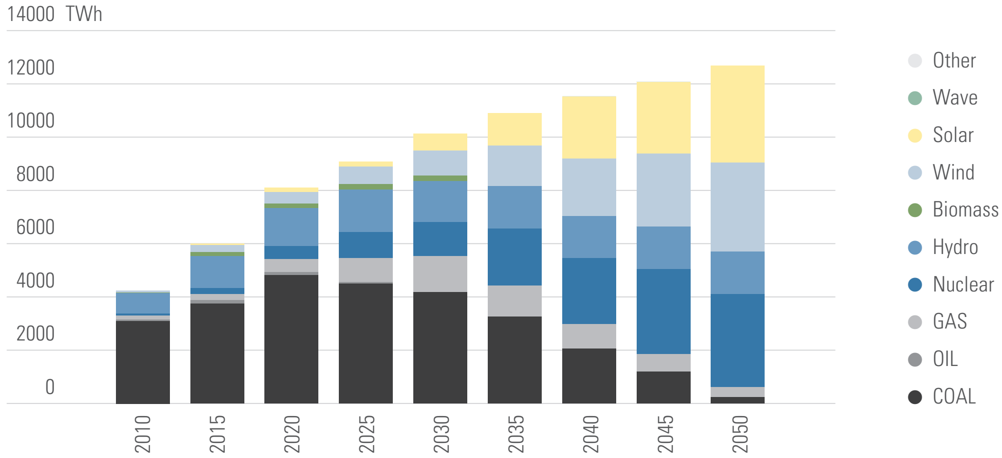
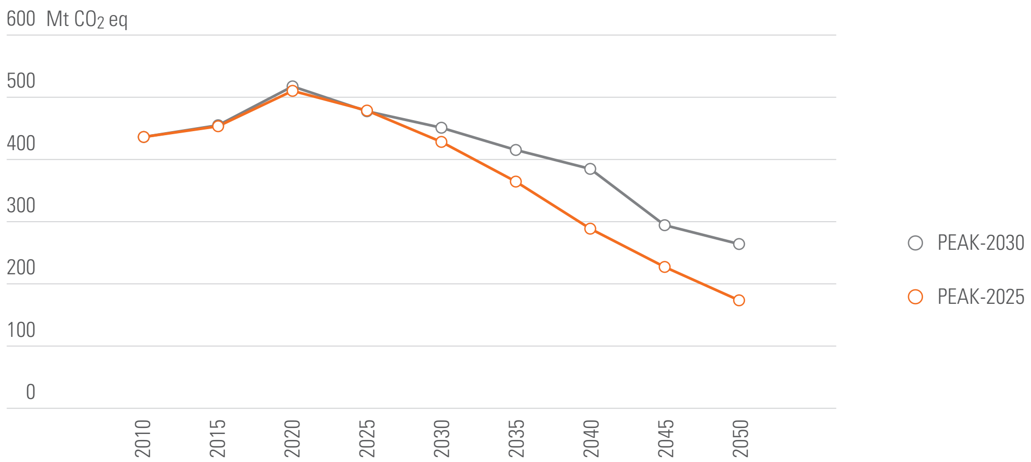


Figure 10. CH_4 emissions from coal mining under peaking scenarios



the withdrawal of backward production capacity. Due to the long-term decentralized management system of the coal industry, it is difficult to truly form a joint force on the withdrawal of backward coal production capacity. There is still a large gap between the phase out implementation and required phase out scale. At present, there are still many small coal mines in China with a capacity below 300,000 t/a, and with severe disasters, depletion of resources, backward technology and equipment, lack of safe production conditions, and inconsistencies with coal industry policies and regulations. The National Energy Administration in 2016 and 2017 respectively proposed to close 1,000 and 500 "backward" coal mines, amount to a total capacity of 60 million tons and 50 million tons. However, the size of backward production capacity withdrawal targets is decreasing, as the difficulty of phase out is increasing. The key policy to phase out coal producing capacity is to establish a market based mechanism so that the backward capacity can exit with a least cost and minimize the economic and social impact. Accompanying compensation policy package also should be implemented given the workers in that sectors generally have low education level and limited employment choice. For those provinces and cities based their local economy on coal resource, a more systematic industrial transformation and upgrading plan should be established to rebuild the local industry. Central government should provide strategic investment or government transfer to help the local government finish the transformation and upgradation.

As a clean, highly efficient and convenient energy carrier, **electric power** will gradually become the major energy type of final energy consumption, indicating that the decarbonization of power sector plays vital part in achieving deep decarbonization pathway. The core tasks of power sector are to achieve the transformation from a thermal power-dominant to a non-fossil fuels dominant system and to achieve wide application of CCUS (Carbon Capture, Utilization and Storage) for the residual fossil fuel generation. On one hand, by launching efforts including phasing out small thermal power generating units with substitutions of highly-efficient power generation technologies, accelerating the construction of power grids for the power transmission to transport decarbonized power from regions of production to key demand centers and other incentive measures favoring non-fossil energies, the share of non-fossil power in total power generation can increase to 34%, 45% and 78% in 2020, 2030 and 2050 respectively.

The electricity sector is facing a serious risk of stranding assets (Fischer, 2015) (Spencer et al, 2017). The risks of new installations of coal based capacity are even higher due to the uncertain electricity demand. But the government is also concerned about whether or not the electricity supply is sufficient enough to support the development of economy in the future (North China Electric University, 2016) (RAP, 2016). Our studies shows that although there is a trade-off between the stranded assets and supply security, the existing coal capacity can supply the most ambitious growth of electricity demand at least till 2025. Thus it will be reasonable to stop all new construction of coal fired power plant in the next five years and reconsider this if the growth of electricity demand is faster than expected. Otherwise, the new constructed power plant will be facing a very serious assets stranding risks.

For the existing coal power plants, almost all stranded assets will happen in government owned plants (including local government owned and central government owned power plants). To reduce the overall amount of stranded assets, an auction mechanism could be considered to identify the least cost options. The carbon market also could be an option to provide financial resources to cover the stranded assets. However, preliminary results shows that the scale of the carbon market is far from enough to cover the stranded assets in the electricity sector. Thus additional financial resource should be identified to cover such cost.

Another option would be for the government to consider requiring coal plant that have depreciated their initial investment value to retire or else be placed in a strategic reserve at a fixed age, say of 20-30 years of operation. This could potentially help to reduce excess capacity, while also providing visibility for investment in clean energy alternatives in the power sector. A strategic reserve has been used in other countries, such as Germany, and has the advantage of ensuring security of supply if demand forecasts are wrong. This idea was explored in Spencer et al (2017), and shown to help reduce the total value of stranded assets in the power sector, while also being consistent with meeting climate goals under a <+2°C scenario for China's power sector. Liberalizing power market pricing in the electricity sector could also help to compensate for asset stranding and provide opportunities for coal plant to be retired or provide ancillary services to the power market instead of baseload power. The **industry sector** will play the leading role in the decarbonization pathway of China as it still serves as the biggest energy consuming sector up to 2050, and its low carbon transition will be mainly realized through such efforts as the industry structure optimization, fuel switching, energy efficiency improvement. On the one hand, by transforming and upgrading traditional industries, speeding up the elimination of excess capacities and supporting the development of strategic and newly-emerging industries, the ratio of primary, secondary and tertiary industry will be optimized from 9.2%, 42.6% and 48.2% in 2010 to 2.2%, 32.5% and 65.3% in 2050. On the other hand, by upgrading the industrial equipment and facilities, applying efficient and innovative technologies, promoting the integrated use of resources and improving the management performance, the efficiency of industry sector will be greatly improved. Through these two efforts, the energy consumption per added-value of industrial output could potentially be cut by about 77% from 2010 to 2050, making the final energy consumption of industry sector only climb 26% while industrial added value expands 430% during this period. At the same time, by fuel switching from coal to gas and enhancing the use of electricity, the shares of gas and electricity in final energy consumption in the industry sector increase from 3% to 21% and 21% to 39% respectively from 2010 to 2050, while that of coal decreases from 61% to 22%.

For industry sectors, the key for coal shift is technology breakthrough in some key sectors such as cement and iron and steel industries. The high cost of electric boilers or furnish is a major barriers for fuel shift in industries. For the iron and steel industry, the charcoal might be an option but its implication on the LULUCF emission is still a concern. Given the limited technology available, another option is to reduce the material demand and reduce the material intensity from the LCA perspective. For example concrete recycling, and develop new material to replace iron and steel in buildings and automobiles. Such demand management policies will have more potential to reduce coal consumption in industries.

The decarbonization of **the building sector** will be achieved by controlling floor area, inhibiting the unnecessary early demolition of buildings, improving energy efficiencies of both buildings and appliances, and optimizing the energy mix. Firstly, by implementing measures to increase the carrying cost of real estate and by enhancing government guidance and information campaigns on low-carbon lifestyle, though the total floor area will continue to rise, its growth rate will be constrained at a relatively low level, with public building area per capita and residential building area per capita reaching about 13 m^2 and 37 m^2 respectively in 2050, similar to current levels in major EU countries (Germany, France). Secondly, with persistently working on energy efficiency improvements such as applying energy efficient technologies and products, continuous retrofitting of existing buildings with energy-saving features and increasing the proportion of green and low-carbon buildings, the energy consumption for heating per unit area in Northern urban areas can be reduced by half from 2010 to 2050. Thirdly, by continuously optimizing the energy mix, the shares of electricity and natural gas in final energy consumption by buildings can be increased to 47% and 27% in 2050 from 24% and 8% in 2010 respectively, while the share of coal is squeezed from 43% in 2010 to 13% in 2050. In general, the increase in both floor area and non-heating household energy consumption per unit of floor area would still exceed the decrease of unit energy consumption for heating, which drives up energy consumption in building sector by 13% in 2050 from their 2010 level. However, thanks to the increasing share of natural gas and renewable energies in total final energy demand and more than 90% reduction in carbon intensity of electricity, the carbon emissions in building sector will reach peak in 2030 and then reduce in 2050.

Coal consumption by residential sectors contribute about 30% of PM2.5 emissions and even much higher share in heating season in the Beijing-Tianjin-Hebei region. To resolve air pollution in northern China, the Ministry of Environmental Protection (MEP) in China promulgated a plan to establish "coal-forbidden district" in Beijing, Tianjin and 26 cities in the provinces of Hebei, Shanxi, Shandong and Henan in August 2017. This policy required about three million household to switch from coal to gas or electricity for heating, cooking and hot water supply in the Beijing-Tianjin-Hebei region. However, the coal ban plan was not just an environmental campaign, but also had important implication on energy choice behavior and household welfare. First, the coal ban plan changes household energy choice by providing gas access through building gas transmission and distribution pipelines. Second, the coal ban plan retrofits coal stoves and coal boilers to diminish coal consumption. Third, in order to reduce coal consumption, the government also provided significant subsidies to households for compensating the increase in energy bill, including subsidizing equipment installment and providing price subsidies for coal-switching households. For reducing household coal consumption, successful policies rely on a solid understanding of the driving forces on energy choice and rapidly growing energy demand in Chinese households, i.e. how household energy consumption responds to the changes in household income, energy price, availability of energy carriers and demographic profiles.

Careful city planning by improving accessibility to clean energy can reduce coal consumption by changing energy choice towards more clean energy consumption behaviors. We highlight the importance of infrastructure availability in residential sectors, thus the energy policy in residential sectors should be considered and coordinated with the broader city planning and infrastructure retrofit policies to allow synergies among them.

The coal consumption at the local level and in the residential sector should not be considered separately form the energy poverty and poverty eradication. Based on household survey data, it is clear that coal consuming families are generally poorer than average, with lower education, lower income, poorer housing with limited access to clean energy. Thus the "energy ladder" hypothesis make sense from that perspective. The economic growth shift households toward clean fuel such as pipe gas and electricity in urban China. The improvement of economic status of poor household in developing countries is key to shift the consumption from dirty fuel such as coal to clean fuel. Coal is an inferior good compared with electricity and gas. Considering a household facing a choice between purchasing coal and other clean fuel (such as pipe gas and electricity). The consumption of both coal and clean energy can meet the requirement of subsistence of this household, but coal consumption has a negative effect on the health and indoor environment. The subsistence will be more important when utility decrease. In this case, as clean energy becomes more expensive, the consumer substitutes coal for clean energy in order to maintain the required subsistence. As coal become cheaper, urban households will consume both more coal and more electricity to go with it. Given the wealth effect fixed, providing subsidies to clean energy might be better policy instrument to encourage fuel shift.

Conclusion

China's energy consumption has recently risen quickly along with the rapid economic growth, from 1.47 billion tons of coal equivalent[1] (tce) in year 2000 to 4.36 billion tce in year 2016, with a yearly growth rate of 7 percent. Coal has dominated China's energy consumption for decades, accounting for around 70 percent of the primary energy supply, which is much higher than the global average. However, the massive use of coal has led to many environmental challenges in China, including serve smog and haze, water resource depletion and greenhouse gas emissions. In particular, exposure to ambient air pollution has been identified as a leading risk factor for global health. It was estimated that 99.6 percent of China's population was exposed to PM2.5 air pollution levels exceeding the World Health Organization guidelines of 10 ug/m^3. Besides the health damages, air pollution also has created economic consequences, such as lowering down housing price, reducing worker productivity and purchasing masks and air pollution filters.

Besides climate, there are therefore a significant number of advantages to phasing down the share of coal in the energy system. The question for China is the speed and manner in which this can be done. These study has therefore illustrated two alternative scenarios, highlighting alternative pathways for a transition to a significantly lower share of coal use in the Chinese energy system: namely, a current "NDC" scenario, and a possible "early peaking" scenario.

China's current NDC requires coal consumption to be peaked around 2020 which will allow for CO_2 peaking around 2030. Under the NDC scenarios, the coal consumption will peak around 2020 around 3.03 Gtce, and then declines by 12.0% to 2.66 Gtce in 2030 and by 45.4% to 1.65 Gtce in 2050. The share of coal in overall primary energy consumption also decreases throughout the whole study period, from 71.7% in 2010 to 46.8% and 29.8% in 2030 and 2050, respectively.

However, under an early peaking scenario, coal consumption could be further reduced after 2020 and lead to an early peaking of CO_2 emissions around 2025. Coal consumption could also peak in 2020 at 2.98Gtce, slightly less than under the NDC scenario, while declines to 2.03Gtce and 1.09Gtce respectively in 2030 and 2050, approximately 135.2Mtce and 563.6Mtce lower than NDC scenario. The whole economy will further lower the share of coal in its primary energy, the share of coal in total primary energy consumption under early peaking scenario is 46.3% and 21.8% in 2030 and 2050, compared to 46.8% and 29.8% respectively in the targeted years under NDC scenario. With this, the early peaking scenario indicates an early CO_2 peaking in year 2025 at 10.2Gt, then will drop down to 9.93Gt in 2030, nearly 0.4Gt lower than the NDC scenario, and 5.7Gt by the end of 2050, about 1.6Gt lower than under the NDC scenario. The early peaking scenario also involves the almost complete phase out of coal from the power sector by 2050. Implementing the early peaking requires more stringent policies to phase out coal in coal production, electricity sector, industries and buildings. Marketization is a key for all sectors to promote energy transition in a least cost manner. The externalities of coal should be internalized so that clean energy can gain competitiveness compared with coal. For coal producing sectors, the labor policy aiming at low education workers is important to soften the social impact on low-income workers. The

1 Electricity is converted by average quantity of fuel used for power generation.

central government would also need to provide transition funds to help local governments reestablish industries and avoid demographic decline.

For the electricity sector, a very large risk of stranded assets is approaching. The government should take immediate action stop building new coal power plants, accelerate the electricity reform and transaction of generation trade to identify least cost options to manage the stranding assets. The coal producing countries should also understand such long-term transition and manage their investment carefully to avoid stranding assets in coal production.

To accelerate the shift from coal to clean energy in industrial sectors, both technology innovation and material conservation can play roles. For some sectors, the demand side management will be critical given the technology options in supply side might be very limited. The coal consumption in building sectors are closely linked with energy poverty and interacts with housing choice and infrastructure availability, the city planning policies together with infrastructure retrofit policy and subsidies for clean energy can contribute to shift away from coal in residential sectors. However, the energy ladder hypothesis remind us that the long-term economic development will be essential for developing countries to abandon coal as an inferior fuel for production and living.

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