京都大学大学院経済学研究科
再生可能エネルギー経済学講座
ディスカッションペーパー

Analyzing the impact of decarbonization policy implementation on China's economy and environment

Analysis using E3ME Macro Econometric Model

2024 年 3 月
March 2024

Zian Chen[a], Sunhee Suk[b], Bence Kiss-Dorbronyi[c], Toru Morotomi[d]

[a] Ph.D. Student, Graduate School of Fisheries and Environmental Sciences, Nagasaki University
[b] Associate Professor, Graduate School of Fisheries and Environmental Sciences, Nagasaki University
[c] Managing Economist, Cambridge Econometrics, Corvinus University of Budapest
[d] Professor, Graduate School of Economics and Faculty of Economics, Kyoto University

Analyzing the impact of decarbonization policy implementation on China's economy and environment

Analysis using E3ME Macro Econometric Model

Zian Chen[a], Sunhee Suk[b], Bence Kiss-Dorbronyi[c], Toru Morotomi[d]

[a] Ph.D. Student, Graduate School of Fisheries and Environmental Sciences, Nagasaki University
[b] Associate Professor, Graduate School of Fisheries and Environmental Sciences, Nagasaki University
[c] Managing Economist, Cambridge Econometrics, Corvinus University of Budapest
[d] Professor, Graduate School of Economics and Faculty of Economics, Kyoto University

Abstract:
As the world's largest emitter of greenhouse gas (GHG), China must implement robust strategies to address the increasing severity of climate change and meet its pledged emission reduction targets. This study uses the E3ME model to simulate the medium to long-term impacts of decarbonization policies, as represented by phasing out coal-fired power generation and the use of carbon pricing, on China's environment and economy. The results indicate that compared with the option of implementing solely regulatory policies (phasing out coal-fired power), the implementation of economic incentives leads to a shift in China's power mix to a much cleaner mode, thus making a greater contribution to CO_2 emission reduction while also having a more significant positive impact on the economy. Moreover, among the three policy scenarios set out in this study, a national carbon market that adopts 100% free allocations and covers all sectors is the mitigation measure with the highest double-dividend effect for China. Therefore, China should focus more on developing and improving its national carbon market, expanding its scale, and achieving full sectoral coverage as soon as possible to facilitate the transition to a low-carbon economy and achieve its pledged emission reduction targets.

Keywords: phasing out coal-fired power generation, carbon pricing, carbon neutrality, E3ME model, power mix, economic impact

1. Introduction

Addressing climate change has become one of the most urgent and important challenges for human beings in the 21st century, and strong action on climate change must be taken as soon as possible. In 2015, the Paris Agreement set out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C[1]. In response to the call of the Paris Agreement, China has announced its intention to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060 (IEA, 2021). As the world's largest emitter of greenhouse gases (GHG), China must implement robust strategies to address the increasing severity of climate change and meet its pledged emission reduction targets.

In order to combat climate change, one important short-term strategy is to rapidly phase-out the use of coal from the global energy system. This includes the phase-out of existing coal-fired power plants. According to a Climate Analytics 2019 report, a phase-out of coal-fired power is necessary to align with the Paris Agreement goal of curbing the global temperature rise to 1.5 °C, and points out that OECD countries must phase out coal-fired power by 2030, and the rest of the world by 2040 (Yanguas-Parra et al., 2019). At COP26, coal-fired power generation was cited as the single biggest cause of global temperature increases, and delegates called for greater efforts to reduce coal-fired power generation and promote the transition to clean energy[2]. Furthermore, a new research titled *Ten New Insights in Climate Science 2023/2024* emphasized that limiting global warming to less than 1.5°C would require shortening the lifespan of existing fossil fuel infrastructure and/or operating assets below normal capacity (Bustamante et al., 2023). China is highly dependent on coal for its electricity supply and has the world's largest as well as growing coal power infrastructure. Specifically, China currently has more than 1,000 GW of coal-fired power capacity, which accounts for about 50% of global coal-fired power capacity (Global Energy Monitor, 2023), and about 61% of its electricity is produced from coal (Pan et al., 2023). For China, therefore, regulation of coal-fired power generation must be instigated in order to achieve its decarbonization goals.

Furthermore, as a key decarbonization strategy expected to achieve China's national climate goals, China launched pilot carbon markets in five major cities and two key provinces in 2013 and is transitioning to a national system (Li et al., 2022). On 16 July 2021, China's national ETS officially began trading on the Shanghai Environment and Energy Exchange (SEEE), covering the power sector, and coverage is planned for seven other high-emission industries (petrochemicals, chemicals, building materials, steel, nonferrous metals, paper, and domestic aviation) during the 14th Five-Year Plan period (2021–2025) (Li et al., 2022). China's national

[1] https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en.

[2] https://webarchive.nationalarchives.gov.uk/ukgwa/20230313120149/https://ukcop26.org/global-coal-to-clean-power-transition-statement/.

carbon market is the world's largest in terms of emissions coverage (more than four billion tCO_2 from the power sector, approx. 40% of national emissions) (Liu & Murun, 2022). Launched in the second half of the year, the national market had a relatively short first compliance cycle, which was completed on December 30th, 2021 (Li et al., 2022). In its first compliance cycle, China's National ETS covered 2,162 key compliance entities with a total annual emissions of around 4.5 billion $t\text{-}CO_2$, i.e., those with minimum emissions of 26,000 tons of carbon dioxide equivalent in any year from 2013 to 2019, including combined heat and power, as well as captive power plants in other sectors (ICAP, 2023). Allocation is currently through free allocation but there are plans to introduce and gradually expand the auction method, revenues from which would be used to further support development of the national carbon market and key GHG reduction projects. Entities subject to the carbon market can use National Certified Voluntary Emission Reduction (CCER) to offset their carbon allowances without exceeding 5% of their carbon allowances (ICAP, 2023). In the first compliance cycle, 179 million tons (cumulative trading volume), with a total transaction value of about 7.66 billion yuan had been traded, with an average trading price of 42.8 yuan/ton (about 6 USD/ton) (Li et al., 2022).

While China's government is actively promoting the development of carbon pricing policy, it is also facing conflicting concerns and pressures related thereto; specifically, whether economic incentives such as carbon pricing will be able to realize a double dividend of positive economic impact and reduced emissions, and whether following the international trend away from coal, which China relies on most for its low-cost power generation, would have a negative impact on the economy. To assist in such decision making, therefore, it is necessary to assess the effectiveness of decarbonization policy implementation.

Several studies have been conducted to analyze the impact of decarbonization policies on China's economy and environment by using the Computable General Equilibrium (CGE) model and Input-Output (IO) model. These include an assessment of decarbonization technologies (Ren et al., 2023; Xiao et al., 2022), EV-related policies (Guo et al., 2021; Lin et al., 2023; Jiang et al., 2022), energy substitution (Lin & Jia, 2020; Jia & Lin, 2021), and low-carbon transition of the power sector (Zhang et al., 2021; Sun et al., 2022; Wang & Fan, 2021). However, the most widespread is assessment of the effects of carbon pricing policies. For example, Li et al. (2018) introduced a CGE model embedded with carbon trading block to research the impact of establishing a national carbon trading market on the power sector by 2030. The main simulation results showed that carbon emissions trading would promote the clean production of electricity and would oblige power industry carbon emissions to peak earlier, but also incur a certain negative impact on the overall economy. Zhao et al. (2018) developed an improved CGE model to evaluate the effects of carbon pricing (carbon tax and carbon emission trading) on the CO_2 emissions, CO_2 emission intensity, output, and energy consumption of China's power sector during 2010–2050. They suggested that a policy combining carbon tax and carbon emission trading can sharply reduce CO_2 emissions and help optimize the energy structure to achieve sustainable development. Lin & Jia (2019) constructed a dynamic recursive CGE model to study the impact of national ETS on the economy, energy, and environment by 2030. They found that national ETS can significantly increase the price of electricity and negatively impact GDP by 0.19–1.44%, and that the emission reduction effect of China's national ETS would increase with time as long as the mechanism of the ETS market remains unchanged. Zhang et al. (2022) used a dynamic CGE model to compare the pure carbon ETS to the hybrid carbon policy (carbon ETS and carbon tax) by clarifying the quantitative gains and losses on carbon emission reduction and the macroeconomic, energy, and environmental impacts under similar carbon peak targets. The result showed that coordinated use of a carbon tax and a carbon ETS can help reach a carbon emissions peak before 2030 and do so at a lower economic cost compared to the effect of pure carbon ETS via the CGE model. Liang et al. (2022) established a 3E-CGE model with dynamic characteristics of the economy-energy system-carbon emission linkage to conduct a scenario simulation and sensitivity analysis on carbon tax, carbon-trading, and climate-friendly technological progress, respectively. They found that the best path for China to achieve its dual carbon goals and economic development in the next 40 years involves effectively combining use of a carbon tax, carbon trading, and progress in climate-friendly technologies. Zhao et al. (2023) used the IO model to investigate the effects of carbon tax on carbon emission reduction and economy in China. Results showed that along with the increases in carbon tax, the inflation rate was increased, the rate of carbon emission reduction was increased, and the negative effects on GDP and employment were also increased.

As mentioned above, there have been several studies assessing the implementation effects of China's decarbonization policies, especially carbon pricing policies. However, few cover regulatory policies such as the phasing out of coal-fired power generation. Lee et al. (eds) (2019) used the E3ME (Energy-Environment-Economy Macro Econometrics) model[3] to simulate the economic impact of phasing out coal-fired power plants and nuclear power plants by 2050 in East Asia (China, Japan, Korea, Taiwan). The analysis showed that despite severe restrictions on the use of nuclear and coal power, the negative impact on the economy is limited, and it is possible to shift to a sustainable power mix with improvement in the economy. However, it does not consider the simultaneous implementation of the phase-out of coal-fired power generation with carbon pricing, and the coal-fired power generation phase-out scenarios were not designed on the basis of the roadmap published by the Government or the findings of relevant studies, thus the design of the policy scenarios lacks a theoretical basis. In conclusion, there is a shortage of research that evaluates the implementation effects of decarbonization policies involving the phasing out of coal-fired power generation in China.

In this context, this study aims to quantitatively study how decarbonization polices, especially the phasing-out of coal fired power plants and carbon pricing, would impact the Chinese economy and environment. The latest version of the E3ME model was used for the impact analysis in this study.

[3] E3ME model features and manual: https://www.e3me.com/features/.

2.Methodology

2.1 Scenario specifications

For the analysis, three hypothetical policy scenarios were designed relative to a baseline scenario. The baseline scenario is normally based on current policies being continued without additional special measures, and in this study it will be used to compare policy scenarios. The E3ME baseline for China has been made consistent with the trends in the Reference Scenario of the IEEJ Outlook 2021, published by the Institute of Energy Economics, Japan.

The Coal_Phaseout scenario is a scenario involving the phasing-out of coal-fired power plants, and was designed based on the following steps. First, data on China's unit-level coal-fired power plants in operation were obtained from Global Energy Monitor (Global Energy Monitor, 2022), which covers a total of 3,129 coal-fired power units including those in Hong Kong, with a combined capacity of about 1,115,018 MW. Of these, data on technology type or year of starting operation of some power generation units (basically captive power units) were not disclosed for some units, thus the coal-fired power generation units in operation in China covered by this study totaled 3,114, including Hong Kong, with a total capacity of about 1,082,136 MW (about 97% of the total capacity). Then, based on the relevant research results, a phase-out roadmap for coal-fired power plants in China was determined. Cui et al. (2019) pointed out that cost-effective pathways for meeting the well-below 2°C or 1.5°C goals require canceling new coal projects and reducing operational lifetimes of existing units to 35 and 20 years, respectively (these targets refer to a number of key countries around the world, including China). Cui et al. (2021) indicated that under the targets of 1.5°C and 2°C, China would need to achieve net zero CO_2 emissions by 2055 and 2070, respectively. To do this, 1) China needs to ensure that no new coal power plants are constructed, as the sooner new construction is stopped, the lower the cost of deep decarbonization in the future. On this basis, 2) China should rapidly shut down those subcritical coal-fired power plants that have been operating for more than 10 years and have a smaller unit size below 600 MW, and 3) allow remaining plants to operate through a minimum guaranteed lifetime of 20 or 30 years, with gradually reduced utilization to achieve 1.5°C or well-below 2°C climate goals, respectively, and complete phaseout by 2045 and 2055.

Therefore, based on the findings of the above two studies, the coal-fired power plant phase-out roadmap for China proposed in this study is as follows: 1) No new construction of coal-fired power plants, and immediate cessation of those under construction; 2) immediate cessation of subcritical coal-fired power plants of smaller unit size below 600 MW that have been operating for more than 10 years; and 3) the shutdown of remaining plants after 20 years of operating. Based on this scenario, all of China's coal-fired power plants are to be phased out by 2042, assuming such phase-out policy starts in 2022 (Fig. 1).

The CP scenario is a national carbon market scenario, based on China's national carbon targets in 2030 and net zero announcements (see Table 1). In this scenario, the carbon pricing policy covers all sectors and adopts 100% free allocation.

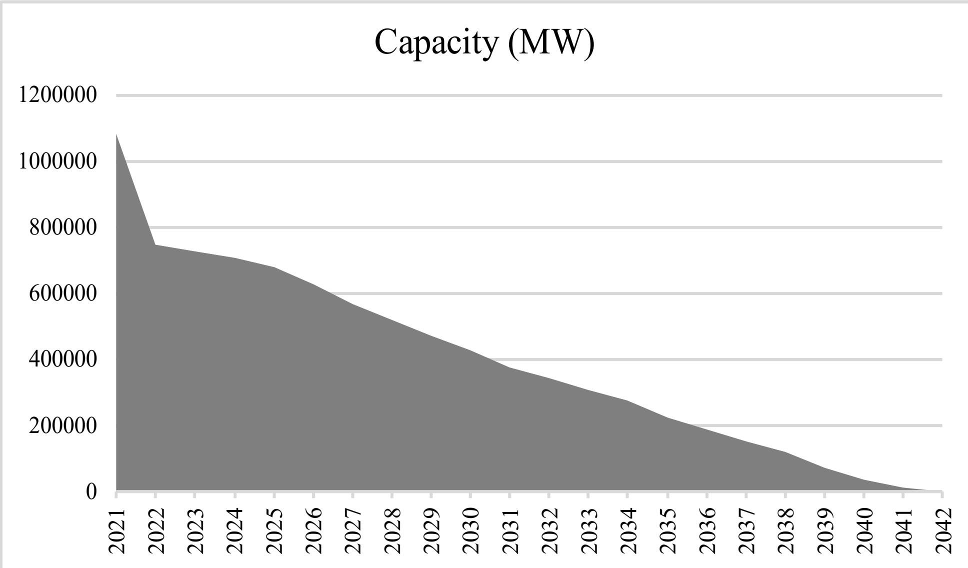


Figure 1. Change in coal power capacity in China under the Coal_Phaseout scenario

The two policy scenarios mentioned above either only consider phasing out coal-fired power generation or only consider carbon pricing. Moreover, the carbon pricing setting in the CP scenario is relatively idealized, which is somewhat different from the actual situation in China. Therefore, this study introduces a CP_Plus scenario addition to the Coal_Phaseout scenario and the CP scenario. The CP_Plus scenario is a policy mix scenario that considers both carbon pricing, as in the above CP scenario, but with more realistic system states (the carbon market setup is similar to the actual situation in China, including limited sectoral coverage, gradual reduction in share of free allocation, as detailed in Table 2) and the phase-out of coal-fired power plants (as in above Coal_Phaseout scenario). In addition, an EV subsidy policy is also considered in this scenario[4].

Table 1. China's emission reduction targets in 2030 and 2060

Target in 2030	Base year	Net zero year
-30%[5]	2020	2060[6]

[4] The purpose of this setting is to ensure that a certain percentage of electric vehicles must exist in the market to better match the actual situation in China. However, the specific value of the subsidy is based on a simple assumption and lacks corresponding evidence. Future research could improve upon this aspect.

[5] China originally aims to reach a carbon peak before 2030; -30% was assumed in this study.

[6] Not modeled beyond 2050.

Table 2. Sectoral coverage and free allocations expected

Sectoral coverage	Free allocations
Energy sector; gradual extension to chemicals, iron, non-ferrous metals, construction materials, paper and domestic aviation starting in 2026.	Up to 70% until 2025, up to 50% until 2030, gradual phase-out until 2035, no free allocations from 2036.

Emissions in this modelling exercise cover only energy-related and processed CO_2 emissions. Non-CO_2 GHG (not modelled) are assumed to fall in line with CO_2 emissions. This study also assumes that non-free allocation of carbon allowances will generate revenues for the government. The revenues are used in three ways, which only applies to the CP_Plus scenario: 40% of total revenues used to reduce the national income tax rate, 40% used for lumpsum payments to households, and the remaining 20% used to invest in energy efficiency, subsidizing renewables and kick start low-carbon technologies. While this is a rather simplified assumption for the use of these new revenues, this approach was chosen to ensure budgetary neutrality.

2.2 E3ME model

The analysis was carried out using the latest version of the E3ME (Energy-Environment-Economy Macro Econometric) model. E3ME is a computer-based model of the world's economic and energy systems and the environment, and is frequently used to assess climate and energy policy through the European Commission's research framework programs. It is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes. Recent E3ME applications include modelling contributions to *Stepping up Europe's 2030 climate ambition Impact Assessment* (55% target) for the European Commission[7], a book titled *Energy, Environmental and Economic Sustainability in East Asia* as mentioned above[8] (Lee et al. (eds) 2019), analysis of China's 2060 net zero targets[9], and recently Japan's 2050 net-zero target (Lee et al., 2022). E3ME is a post-Keynesian, non-equilibrium economic model at its core, built on a simulation approach and econometric estimations. The model is suitable for assessing both short- and long-term impacts and is not limited by many of the restrictive assumptions common to the CGE model. In practice, this means that reaching climate neutrality will not by assumption result in an additional burden to the economy. Instead, the economic impact depends on the use of available resources and their interaction with economic production.

7 https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/impact_en.pdf
8 Energy, Environmental and Economic Sustainability in East Asia | Taylor & Francis Group
9 https://www.carbonbrief.org/analysis-going-carbon-neutral-by-2060-will-make-china-richer

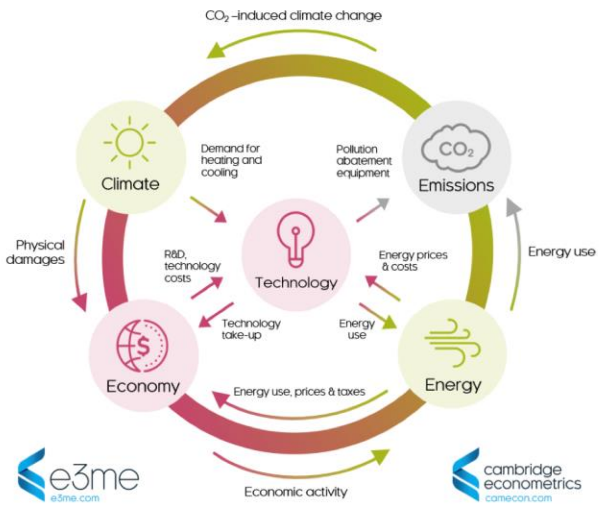


Figure 2. E3ME model

Source: E3ME Model Manual v9.0, Cambridge Econometrics, 2019.

3. Results

3.1 Carbon price, power mix and CO_2 emissions pathways

A high carbon price level is needed to achieve emission reduction targets in China (Fig. 3). Carbon prices are higher in the scenario with more realistic policy settings (CP_Plus scenario). This may be due to the different settings of the two carbon pricing scenarios. For example, in the CP_Plus scenario, carbon pricing has limited sectoral coverage. This means that abatement occurs in a limited area, and higher incentives for abatement may be required to achieve the mitigation target. Also, the free allocation has been phased out in the CP_Plus scenario, implying that firms must pay directly for carbon allowances, thereby immediately assigning a cost to carbon emissions that is reflected in the final carbon price. To achieve the 2030 target, the carbon price is around 115 USD/tCO_2 and 249 USD/tCO_2 in the CP and the CP_Plus scenario, respectively. In order to reach the net zero goal, carbon prices need to be set at a further higher level. Prices in 2050 are 408 and 439 USD/tCO_2 respectively in the CP scenario and the CP_Plus scenario.

Furthermore, the trajectory of carbon price change under the CP_Plus scenario is unstable before 2040. In the CP_Plus scenario, the internal setting of carbon pricing changes until 2036 (share of free allocation, number of sectors covered), combined with the setting of phasing out coal-fired power generation by 2042, which exogenously affects the energy (power) sector covered by carbon pricing (which lasts until 2042), and thus affects the carbon price. The reason why the carbon price trajectory in the CP_Plus scenario stabilizes after 2040 and becomes similar to that in the CP scenario is because the influencing factors mentioned above disappear by around 2040; that is, the internal setting of carbon pricing no longer varies, and the phasing out of coal-fired power generation comes to an end. Additionally, because the CP scenario's settings are relatively stable, this also leads to a relative stable trend in its carbon price fluctuations.

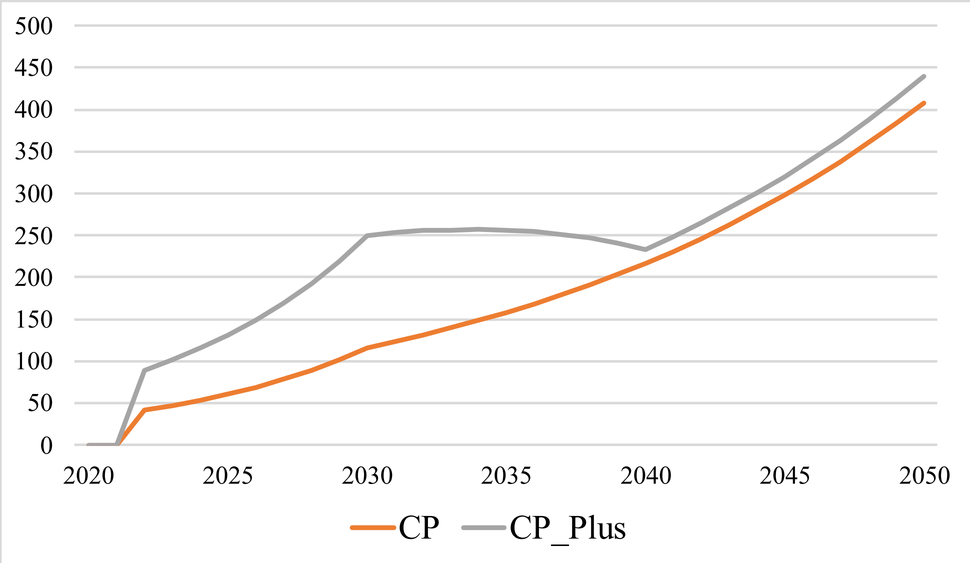
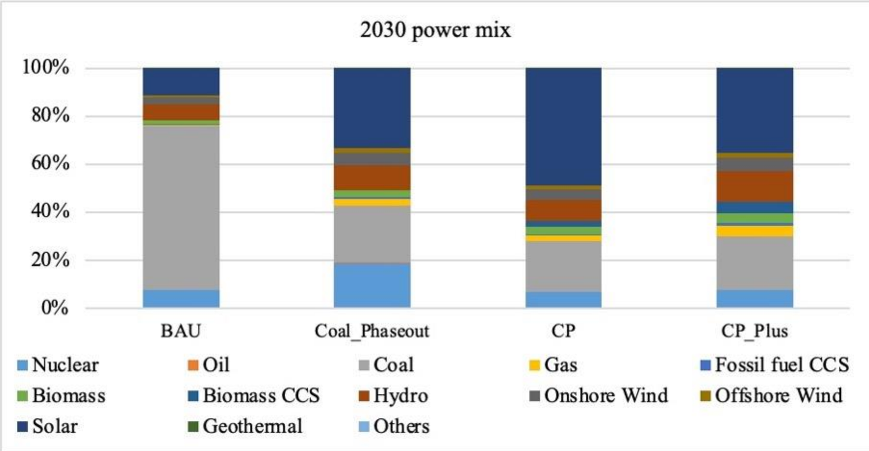


Figure 3. Carbon price (USD/tCO_2 (2010))

Regarding the impact on the power mix (Fig. 4), even without phasing out coal-fired power plants (CP scenario), the proportion of electricity generated by coal decreases significantly, from 70.9% in 2021 to 21% in 2030 and 1.3% in 2050. In the CP and the policy mix scenario (CP_Plus scenario), solar, biomass CCS, and nuclear have mainly replaced coal and gradually become the main sources of electricity. In the CP scenario, solar, biomass CCS and nuclear power account for about 66.7%, 11.2% and 14.0% in 2050's power mix, and in the CP_Plus scenario, these proportions are 55.8%, 21.0% and 15.6% respectively.

In the instance of sole use of a coal regulation policy (Coal_Phaseout scenario), coal-fired power is mainly replaced by solar, nuclear, and gas-fired power, accounting for about 40.7%, 31.9% and 19.9% in the 2050 power mix. In the long term, the three scenarios described above lead to a shift away from a coal-based to a solar-based power mix in China. However, in the Coal_Phaseout scenario, natural gas also replaces a part of the proportion related to the phase-out of coal, accounting for about 20% of the power mix in 2050. This is the reason that CO_2 emissions have not been further reduced after the phase-out of coal-fired power generation (Fig. 5). Compared to 2021, after a 25.1% reduction in carbon dioxide emissions in 2040, the rate of emissions reduction starts to decrease, and by 2050 the reduction rate is 16.1%. In the long term by 2050, while phasing out coal-fired power generation could contribute to CO_2 emissions reductions, it falls far short of the national mitigation target and is much less effective than the implementation of economic incentives.



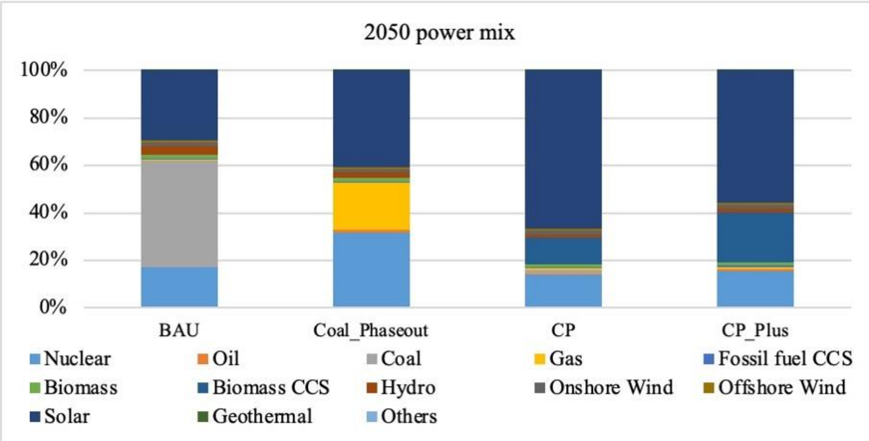


Figure 4. Impact on 2030 and 2050 power mix

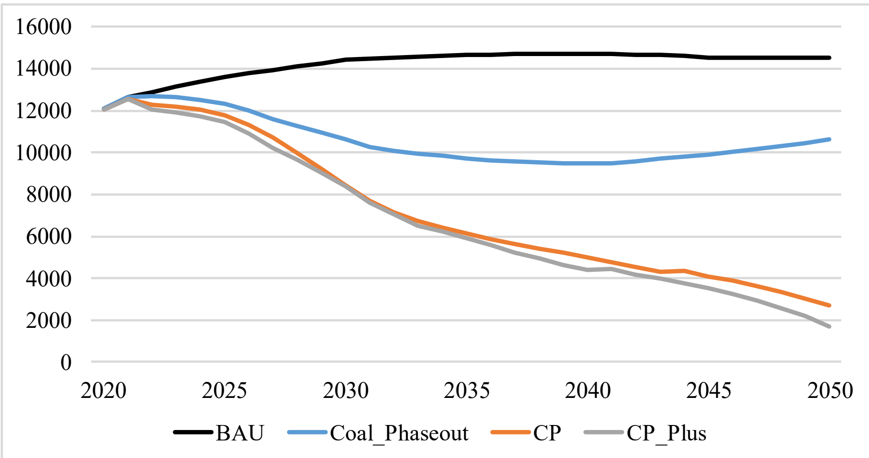


Figure 5. CO_2 emissions pathways under different scenarios

3.2 Economic impacts

The GDP impacts of each scenario are given in Fig. 6. Viewing the period 2022–2050 as a whole, all cases have a positive impact on GDP (compared to the baseline scenario). There is a 0–2.1% positive impact on GDP in the Coal_Phaseout scenario between 2022 and 2042, and a 0–0.2% negative impact on GDP from 2042 to 2050. When considering the GDP gain/loss of the coal-fired power phase-out for the entire 2022–2050 period, the positive impact on GDP exceeds the negative impact on GDP.

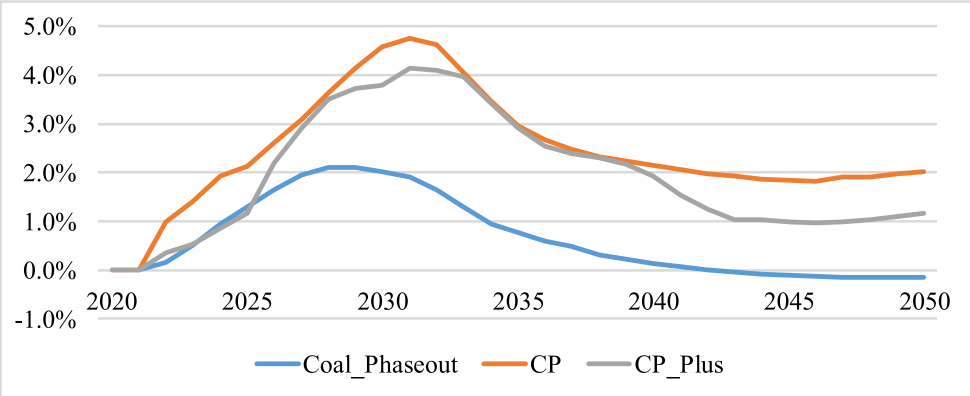
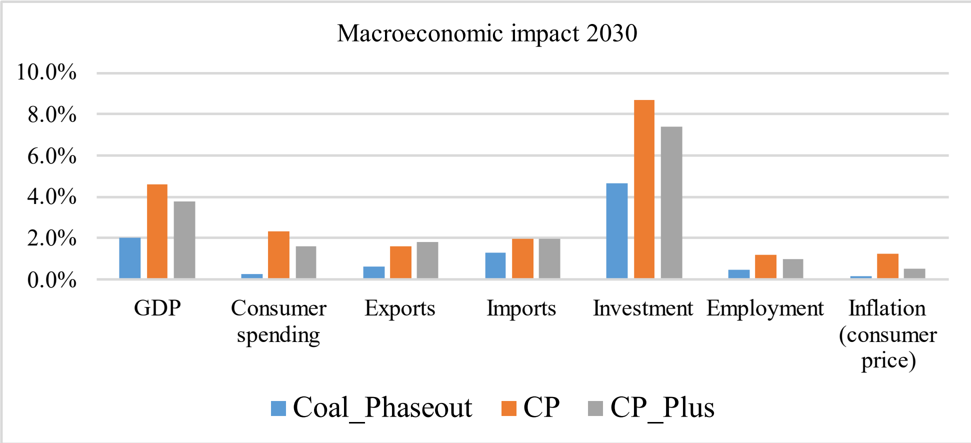


Figure 6. GDP impacts of the three scenarios (% difference from baseline)

The positive impact on GDP is greater with the implementation of economic incentives (CP and CP_Plus scenario) compared to the implementation of only the phase-out of coal-fired power generation (Coal_Phaseout scenario), while the positive impact on GDP of the policy mix scenario (CP_Plus scenario) is relatively lower than that of the carbon pricing-only scenario (CP scenario). In the CP_Plus scenario, while the government could generate revenue from the carbon allowances auction and use it to stimulate the economy, in the short term the negative economic impact of moving away from coal, which China chiefly relies on for its lowest-cost electricity generation, would reduce the stimulus effect of revenue recycling. Moreover, the sectoral coverage of carbon pricing in the CP_Plus scenario is limited, which means the implementation of carbon pricing will induce low carbon investment in fewer sectors.

The breakdown of GDP impact is given in the charts below (Fig. 7). In all scenarios, the growth of GDP is mainly driven by the additional investment induced by decarbonization policies. Compared to the implementation of only the phase-out of coal-fired power generation, the implementation of economic incentives has a stronger inducing effect on investment, and this is the main reason why economic incentives have a more significant positive impact on GDP. In the Coal_Phaseout scenario, there is a slightly negative impact on GDP after 2042, mainly due to reductions in employment and investment.



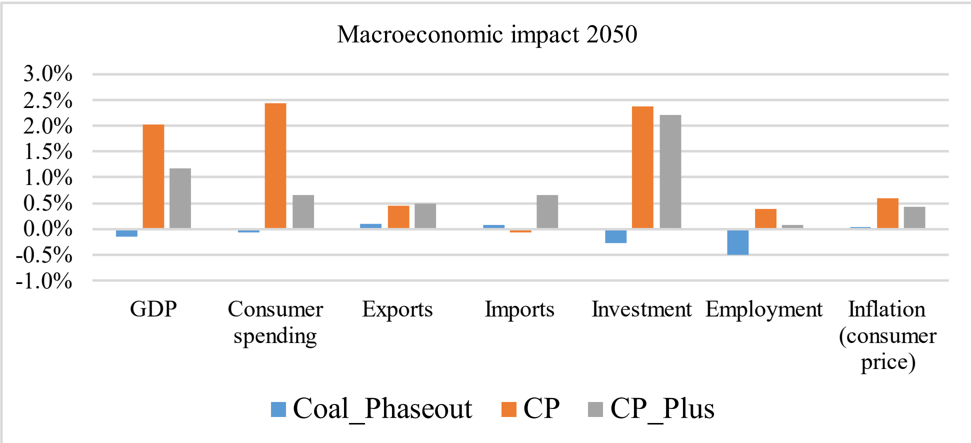
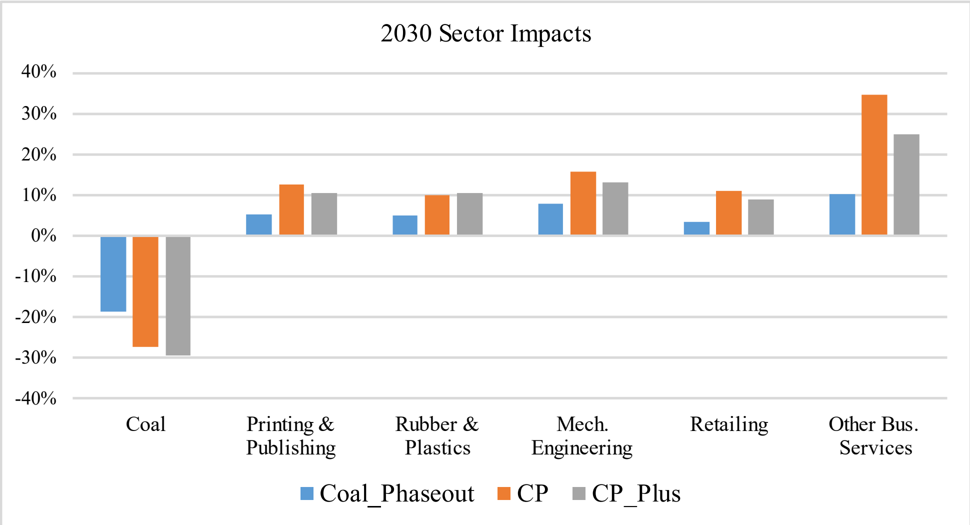


Figure 7. Breakdown of GDP impacts by components of GDP in 2030 and 2050 (% difference from baseline)

Due to the CP_Plus scenario's limited sectoral coverage, the overall positive impact of investment in CP_Plus is slightly lower, despite the possibility of raising government revenue from the allocation which could be directed at additional energy efficiency investment. Additionally, although under the CP_Plus scenario the government can stimulate consumption through using additional carbon revenues (reduce income tax, lumpsum payments to households), this does not result in a significant increase in consumer spending. This can be attributed to the higher carbon price in the CP_Plus scenario and the loss of employment due to the phase-out of coal-fired power plants.

The impact on the output of sectors under the three scenarios is shown in Fig. 8. The model simulation indicates that the coal sector is significantly negatively impacted in all three scenarios. However, the implementation of economic incentives (CP and CP_Plus scenarios) leads to a much higher reduction in output of the coal sector compared to the implementation of only the phase-out of coal-fired power generation (Coal_Phaseout scenario). Specifically, in the Coal_Phaseout scenario, the differences between output in the coal sector and the baseline are -18.7% and -36.3% in 2030 and 2050, respectively, while in the CP and CP_Plus scenarios these are -27.2% and -29.3% in 2030, respectively, deepening to -56.6% and -57.6% in 2050. It is worth noting that the difference between the CP scenario and the CP_Plus scenario is very small. This indicates that even if economic incentives are implemented along with mandatory regulations like the phase-out of coal, the limited sectoral coverage by carbon pricing prevents further reductions coal sector output, as sectors not covered by carbon pricing will not switch away from low-cost, high-emission coal for their production activities.



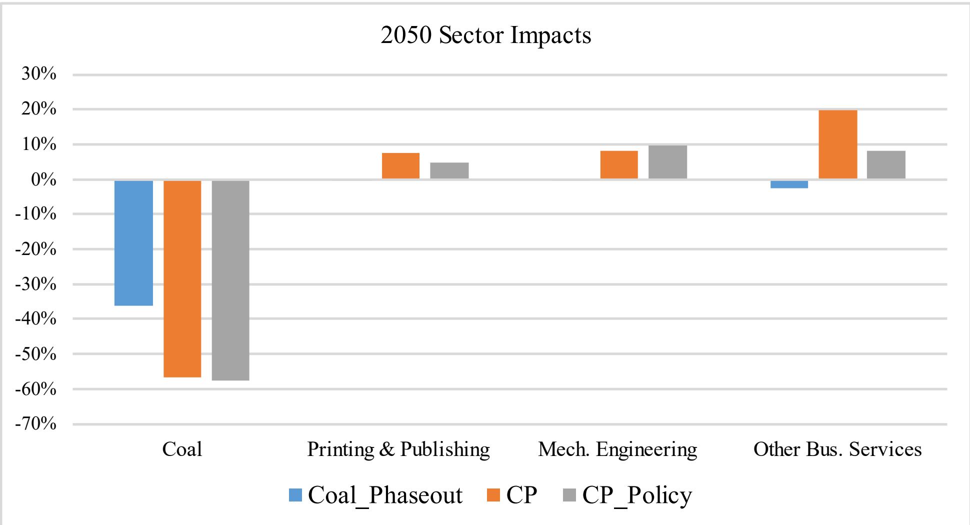


Figure 8. Impact on sector output in 2030 and 2050 (% difference from baseline)

It is worth noting that carbon pricing, as a market mechanism, affects the behavior of firms and consumers through price signals, thus inducing a range of direct and indirect economic impacts across different sectors. The business services sector is significantly positively impacted in the CP and CP_Plus scenarios, especially by 2030, with differences from the baseline of 34.6% and 24.5% in 2030, respectively. This is because the business services sector provides services for carbon pricing (including carbon emissions monitoring, reporting, and services) and also provides technical advice, technical support, and other services for low-carbon technology innovation. Similarly, due to the limited sectoral coverage, the output of business services is less impacted in the CP_Plus scenario.

In addition, output in a number of other sectors is also positively affected. For example, the mechanical engineering sector may benefit as carbon pricing leads to a greater level of technological innovation by firms, which drives the production of more energy-efficient and lower-emission equipment and machinery, and thus contributes to the sector's growth. Carbon pricing also leads to an increase in the cost of fossil energy, which in turn drives a shift in production and consumption patterns. Consumers may switch to greener, more energy-efficient products and services, which would stimulate growth in related industries; for example, the plastics and rubber sector may increase production of environmentally friendly materials. As investment in the low-carbon economy increases, the printing and publishing sector may benefit from an increase in publications with environmental and sustainability themes. At the same time, the service sector, such as retail, may also benefit from increased consumer demand for greener products, as well as the development of emerging green product and service markets.

4. Conclusion

This study simulates the medium to long-term impacts of decarbonization policies, represented by the phasing out of coal-fired power generation and carbon pricing, on China's environment and economy through the E3ME model, aiming to provide valuable references for policymakers. The results show that ambitious policies like the early phase-out of coal-fired power, which are increasingly advocated by the international community, do not have a negative impact on China’s economy, but have a limited contribution to CO_2 emission. In contrast, the implementation of economic incentives leads to 1) a shift in China's power mix to a much cleaner mode, 2) a greater contribution to CO_2 emission reduction, and 3) a more significant positive impact on the economy while also reducing output from the fossil fuel-related sector more significantly.

Furthermore, as can be seen by comparing the two scenarios where economic incentives are both implemented (CP scenario and CP_Plus scenario), the level of sectoral coverage of carbon pricing appears to be more crucial than the revenue recycling mechanism of carbon pricing and the implementation with or without other decarbonization policies. The CP_Plus scenario is a policy mix scenario that not only considers carbon pricing in line with the reality of China but also incorporates gradually phasing out strong policies such as coal-fired power generation. However, from the results, its overall effect is inferior to the CP scenario. On the basis of carbon pricing already covering the energy sector (electricity generation), giving additional mandatory regulatory measures to this sector exogenously does not seem to be efficient. In contrast, regarding the CP scenario, even without the assumption of revenue recycling and the implementation of additional decarbonization policies such as phasing out coal-fired power generation and EV subsidies, the implementation of a national carbon market with 100% free allocation covering all sectors alone could have the most significant positive impact on the economy while also achieving emission reduction targets.

In summary, among the three policy scenarios set out in this study, a national carbon market scenario that adopts 100% free allowances and covers all sectors (CP scenario) is the mitigation measure with the highest double-dividend effect for China. Therefore, China should focus more on developing and improving the national carbon market, expanding its scale, and achieving full sectoral coverage as soon as possible to facilitate the transition to a low-carbon economy and achieve its pledged emission reduction targets.

The above summarizes the key findings and conclusions of this study, but there are also some areas that need further refinement and improvement in the future research. Firstly, as mentioned in the article, we considered the EV subsidy policy in the policy mix scenario to ensure that a certain percentage of EV must exist in the market to better match the actual situation in China. However, the specific value of the subsidy is based on a simple assumption and lacks corresponding evidence, so the future research could improve on this aspect. Secondly, future research should also consider more diverse decarbonization policies, such as feed-in tariffs, subsidies for renewable energy and low-carbon technology, to provide a more comprehensive range of policy mix scenarios and greater definition. Moreover, while the policy for the early phase-out of coal-fired electricity generation appears robust and ambitious, its efficacy in reducing emissions falls short of expectations. Therefore, future research should delve into a broader spectrum of phase-out strategies and contemplate scenarios where these varied strategies are integrated with a range of other decarbonization policies.

Acknowledgement

This study was conducted with support from the Research Grant for Planetary Health 2023, Faculty of Environmental Science, Nagasaki University and a grant from the Renewable Energy Economics Course of the Graduate School of Economics, Kyoto University.

References

Bustamante, M., Roy, J., Ospina, D., Achakulwisut, P., Aggarwal, A., Bastos, A., Broadgate, W., Canadell, J. G., Carr, E. R., Chen, D., Cleugh, H. A., Ebi, K. L., Edwards, C., Farbotko, C., Fernández-Martínez, M., Frölicher, T. L., Fuss, S., Geden, O., Gruber, N., … Zscheischler, J. (2023). Ten New Insights in Climate Science 2023/2024. *Global Sustainability*, 1–58. https://doi.org/10.1017/sus.2023.25.

Cui, R. Y., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M. R., Sen, A., Song, K., Bowman, C., Clarke, L., Kang, J., Lou, J., Yang, F., Yuan, J., Zhang, W., Zhu, M. (2021). A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature Communications*, *12*(1), 1468. https://doi.org/10.1038/s41467-021-21786-0.

Cui, R. Y., Hultman, N., Edwards, M. R., He, L., Sen, A., Surana, K., McJeon, H., Iyer, G., Patel, P., Yu, S., Nace, T., Shearer, C. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. *Nature Communications*, *10*(1), 4759. https://doi.org/10.1038/s41467-019-12618-3.

Guo, Z., Li, T., Peng, S., Zhang, H. (2021). Environmental and economic consequences of the incentive policy on electric vehicle industry: A CGE based study in China. *Resources, Conservation and Recycling*, *169*, 105542. https://doi.org/10.1016/j.resconrec.2021.105542.

Global Energy Monitor (2023). Global Coal Plant Tracker. https://globalenergymonitor.org/projects/global-coal-plant-tracker/. (assessed June 30, 2023).

Global Energy Monitor (2022). Tracker Map. https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/. (assessed July~October, 2023).

IEA. (2021). An energy sector roadmap to carbon neutrality in China. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china. (accessed April 13, 2023).

ICAP (2023). China National ETS. https://icapcarbonaction.com/en/ets/china-national-ets. (assessed June 30, 2023).

Jia, Z., Lin, B. (2021). How to achieve the first step of the carbon-neutrality 2060 target in China: The coal substitution perspective. *Energy*, *233*, 121179. https://doi.org/10.1016/j.energy.2021.121179.

Jiang, H., Xue, M., Liang, Q., Masui, T., & Ren, Z. (2022). How do demand-side policies contribute to the electrification and decarburization of private transportation in China? A CGE-based analysis. *Technological Forecasting and Social Change*, *175*, 121322. https://doi.org/10.1016/j.techfore.2021.121322.

Lee, S., Pollitt, H., Fujikawa, K. (eds.) (2019) Energy, Environmental and Economic Sustainability in East Asia: Policies and Institutional Reforms, Routledge, London.

Lee, S., He, Y., Suk, S., Morotomi, T., Chewpreecha, U. (2022). Impact on the power mix and economy of Japan under a 2050 carbon-neutral scenario: Analysis using the E3ME macro-econometric model. *Climate Policy*, *22*(7), 823–833. https://doi.org/10.1080/14693062.2022.2061406.

Li, J., Yao, Y., Wang, X. (2022). The first compliance cycle of China's National Emissions Trading Scheme: Insights and implications. *Carbon Neutrality*, *1*(1), 34. https://doi.org/10.1007/s43979-022-00035-3.

Li, W., Zhang, Y., Lu, C. (2018). The impact on electric power industry under the implementation of national carbon trading market in China: A dynamic CGE analysis. *Journal of Cleaner Production*, *200*, 511–523. https://doi.org/10.1016/j.jclepro.2018.07.325.

Liang, S., Lin, X., Liu, X., Pan, H. (2022). The Pathway to China's Carbon Neutrality Based on an Endogenous Technology CGE Model. *International Journal of Environmental Research and Public Health*, *19*(10), 6251. https://doi.org/10.3390/ijerph19106251.

Lin, B., Jia, Z. (2019). What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study. *Energy Economics*, *78*, 301–311. https://doi.org/10.1016/j.eneco.2018.11.030.

Lin, B., Jia, Z. (2020). Economic, energy and environmental impact of coal-to-electricity policy in China: A dynamic recursive CGE study. *Science of The Total Environment*, *698*, 134241. https://doi.org/10.1016/j.scitotenv.2019.134241.

Lin, Z., Wang, P., Ren, S., Zhao, D. (2023). Economic and environmental impacts of EVs promotion under the 2060 carbon neutrality target—A CGE based study in Shaanxi Province of China. *Applied Energy*, *332*, 120501. https://doi.org/10.1016/j.apenergy.2022.120501.

Liu, X., Murun, T. (2022). Carbon pricing for the transition toward net-zero of Asia. *IGES Working Paper*. https://www.iges.or.jp/en/pub/cp-asia/en.

Hannah Ritchie, Max Roser, Pablo Rosado (2022) - "Energy". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy' [Online Resource]. (assessed June 30, 2023).

Pan, X.; Ma, X.; Zhang, Y.; Shao, T.; Peng, T.; Li, X.; Wang, L.; Chen, W. (2023) Implications of Carbon Neutrality for Power Sector Investments and Stranded Coal Assets in China. *Energy Econ*, *121*, 106682. https://doi.org/10.1016/j.eneco.2023.106682.

Ren, M., Ma, T., Fang, C., Liu, X., Guo, C., Zhang, S., Zhou, Z., Zhu, Y., Dai, H., Huang, C.

(2023). Negative emission technology is key to decarbonizing China's cement industry. *Applied Energy*, *329*, 120254. https://doi.org/10.1016/j.apenergy.2022.120254.

Sun, D., Liu, Y., Yang, X., Lyu, L., Yuan, J. (2022). Economic and employment effects of China's power transition based on input–output and scenario simulation. *Advances in Climate Change Research*, *13*(5), 721–728. https://doi.org/10.1016/j.accre.2022.09.001.

Wang, Z., Fan, W. (2021). Economic and environmental impacts of photovoltaic power with the declining subsidy rate in China. *Environmental Impact Assessment Review*, *87*, 106535. https://doi.org/10.1016/j.eiar.2020.106535.

Xiao, K., Yu, B., Cheng, L., Li, F., Fang, D. (2022). The effects of CCUS combined with renewable energy penetration under the carbon peak by an SD-CGE model: Evidence from China. *Applied Energy*, *321*, 119396. https://doi.org/10.1016/j.apenergy.2022.119396.

Paola A. Yanguas Parra, Gaurav Ganti, Robert Brecha, Bill Hare, Michiel Schaeffer, Ursula Fuentes. (2019) Global regional coal phase-out requirements of the Paris Agreement Insights from the IPCC Special Report on 1.5℃, Climate Analytics. https://climateanalytics.org/media/report_coal_phase_out_2019.pdf.

Zhang, T., Ma, Y., Li, A. (2021). Scenario analysis and assessment of China's nuclear power policy based on the Paris Agreement: A dynamic CGE model. *Energy*, *228*, 120541. https://doi.org/10.1016/j.energy.2021.120541.

Zhang, Y., Qi, L., Lin, X., Pan, H., Sharp, B. (2022). Synergistic effect of carbon ETS and carbon tax under China's peak emission target: A dynamic CGE analysis. *Science of The Total Environment*, *825*, 154076. https://doi.org/10.1016/j.scitotenv.2022.154076.

Zhao, A., Song, X., Li, J., Yuan, Q., Pei, Y., Li, R., Hitch, M. (2023). Effects of Carbon Tax on Urban Carbon Emission Reduction: Evidence in China Environmental Governance. *International Journal of Environmental Research and Public Health*, *20*(3), 2289. https://doi.org/10.3390/ijerph20032289.

Zhao, Y., Li, H., Xiao, Y., Liu, Y., Cao, Y., Zhang, Z., Wang, S., Zhang, Y., Ahmad, A. (2018). Scenario analysis of the carbon pricing policy in China's power sector through 2050: Based on an improved CGE model. *Ecological Indicators*, *85*, 352–366. https://doi.org/10.1016/j.ecolind.2017.10.028.