CHEMICAL ENGINEERING TRANSACTIONS
VOL. 106, 2023

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

ISBN 979-12-81206-05-2; **ISSN** 2283-9216

DOI: 10.3303/CET23106059

Economic Impacts of Decarbonization in Power Sector from the Perspective of Carbon Neutrality: A Case Study of Shanxi Province

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China's 2060 carbon neutrality target requires coal-fired power generation and coal consumption to shrink dramatically, or to introduce carbon capture, storage and utilization technologies (CCUS). In the provinces which produce a lot of coal and export it to other regions such as Shanxi Province, there are many severe challenges to achieve carbon neutrality goal. This paper constructs a provincial level Computable General Equilibrium Model for Shanxi Province to estimate the impacts on economy based on different decarbonization scenarios in power sector. Through comparison among the quantified scenarios, a sustainable pathway to coal phasing-out is also discussed in this research. The results indicate that in the simple phasing-out of coal thermal power scenario and single deployment of CCUS technology scenario, it will be a shock to GDP due to its coal-reliance economy. In the scenario which utilizes CCUS technologies and coal phasing out in the future, it proves that CCUS will mitigate economic impacts from 2025 to 2050. So, instead of coal phasing out, a sustainable pathway with accelerating change to thermal coal with CCUS is discussed in this research. It found that in this scenario, Shanxi province can keep a lower carbon intensity with a lowest carbon reduction cost of 3.62 k RMB/t.

1. Introduction

With the proposal of the goal of carbon peak before 2030 and carbon neutrality in 2060, China will strictly control the growth of coal consumption during the "14th Five-Year Plan" period (2020-2025), and gradually reduce it during the "15th Five-Year Plan" period (2026-2030) (Qin et al., 2021).

As an important energy production and export area in China, Shanxi Province is now the largest coal production province in China. Its production of raw coal is 1.063 billion t, which accounts for 27.68 % of the national output. The coal industry is the main contributing industry for Shanxi province. The added value of the coal industry in Shanxi Province increased by 8.4 % year-on-year, while the GDP increased by 3.6 % year-on-year. The growth rate of the added value of the coal industry in Shanxi province far exceeds the growth rate of local GDP (SPDRC, 2022).

For Shanxi province's situation, a study discussed its carbon peak in 2030 by the controlment coal consumption. It proposed that a rapid transition to clean energy supply and energy efficiency improving can strive to achieve carbon peak in 2025 (Qin et al., 2021). A previous study emphasized the importance of coal phasing- out and renewable energy in power sector, by utilizing the TIMES model to simulate carbon neutrality scenario with carbon constraint (Liu, 2021). Another research simulated carbon neutrality in Shanxi province based on LEAP and CA-Markov model. And it is noting that if Shanxi Province strives to decrease carbon intensity, with 80 % of non-fossil energy generation, it has the potential to achieve the carbon neutrality target. It proposed that the CCUS technology can significantly accelerate the achievement of the target (Li et al., 2022). Theses research show the technical feasibility and potential of carbon neutrality in Shanxi Province. When compared with other provinces, Shanxi Province will face greater challenges in reducing emissions. The coal control and emission reduction measures implemented by the government will have a greater impact on Shanxi Province's social economy. This paper will assess economic impacts of decarbonization in power sector of Shanxi province and discuss the sustainable pathway with CCUS technology.

Paper Received: 14 June 2023; Revised: 15 September 2023; Accepted: 26 September 2023
Please cite this article as: Han Y., Masui T., 2023, Economic Impacts of Decarbonization in Power Sector from the Perspective of Carbon Neutrality: A Case Study of Shanxi Province, Chemical Engineering Transactions, 106, 349-354 DOI:10.3303/CET23106059

2. Methodology and data

2.1 Computable general equilibrium model

Computable general equilibrium (CGE) models are a class of economic models that use actual economic data to estimate how an economy might react to changes in policy, technology or other external factors. Its production function, utility function and trade are connected to the market and interact with each other through the price mechanism (Malahayati and Masui, 2021). The model structure of CGE model can be described as Figure 1.

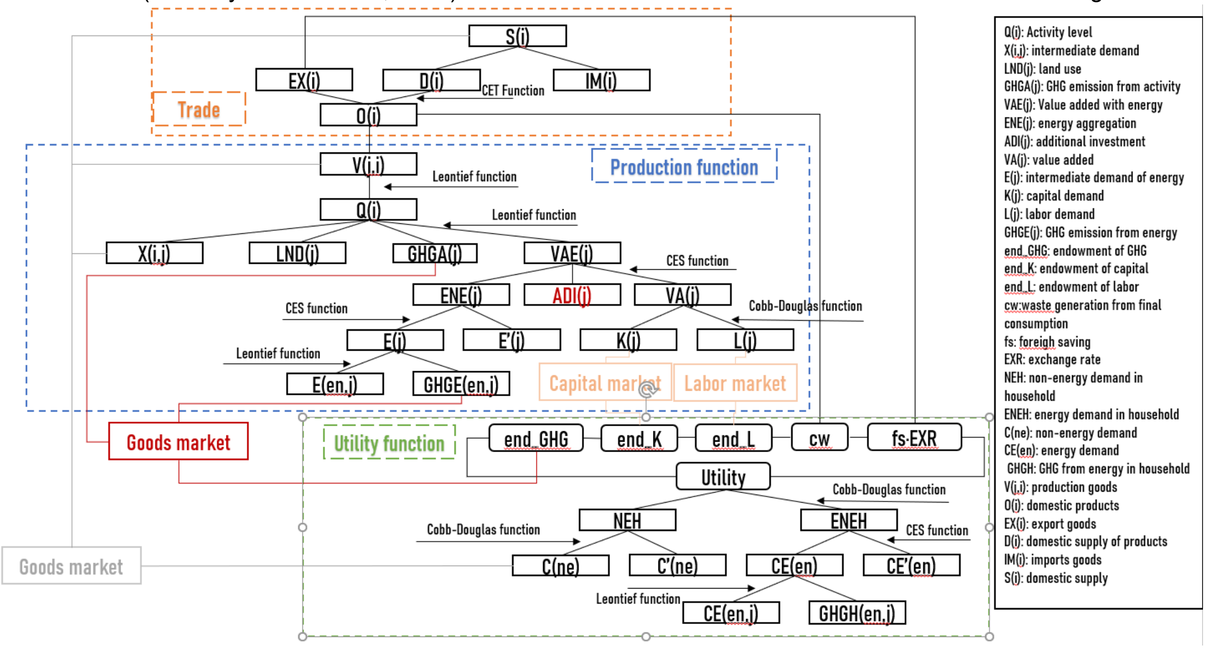

Figure 1: Computable General Equilibrium model structure

This research constructed a provincial level model based on this structure to apply for Shanxi province case. In order to assess the introduction of CCS technology. A part of additional investment has been introduced in the value-added part with CES function.

2.2 Data source

The basic input-output table of Shanxi province (42 sectors) is obtained from the yearbook of China Regional Input-Output Table 2017. And they are aggregated to 20 sectors as shown in Table.1.
Other detailed factors, such as the labour, population, GDP, power generation, energy production and consumption are derived from National Economic and Social Development Statistical Bulletin of Shanxi province in each year. The carbon emission factors refer to China's carbon emission accounts (Shan et al., 2018).
And to introduce the CCUS technology, the certain sector will require additional investment to provide equipment and transportation, and maintenance cost on electricity demand. The cost is summarized in Table.2.

2.3 Scenario

For achieving carbon peak and carbon neutrality, to decarbonize the energy system is necessary, which requires the power system to be zero-carbon in 2060. Many research suggest that developing renewable energy is the main path for Shanxi's power sector to achieve carbon neutrality (Liu and Yao, 2021) The 14th five-years plan for Shanxi province also proposes the emphasis on its wind and solar power deployment, which Shanxi's capacity of wind power and solar power will be 30 GW and 50 GW (SPDRC, 2022). Based on this, the scenarios are conducted based on the different power structure.
The BaU (Business as usual) scenario is describing the condition when China does not do any other mitigation actions in the future. But with the progress of social development, the efficiency of energy technology will improve by 2 % per year, while the efficiency of power sector will improve by 1 % per year, which is followed with the historical statistic data from China's statistic book. And due to the dependence of coal, Shanxi province's main source of power generation will be still coal.
The CPO (Coal phase-out) scenario is focusing on the coal-fired power's transition to renewable energy. The capacity of coal-fired power will reach the peak of 85.78 GW in 2030. Wind and solar power will reach 45 GW

and 80 GW respectively in 2030. The coal the coal-fired power will be phased-out in 2060, while the wind and solar power will keep a rapid development, reach 140 GW and 305 GW respectively in 2060.Then to introduce the CCUS technology, and to compare with coal phasing out scenario, two more scenarios are conducted based on existing scenarios: BaU_C scenario and CPO_C scenarios. The main setting is the similar with their respective scenarios, but they will deploy the CCUS technology followed as the reference pathway (Li et al., 2022). The deployment degree of CCUS technology in Shanxi province in the future is shown in Table 3. By deploying CCUS technology, the sector can capture the carbon by 90 %.

This research also discusses the sustainable pathway for Shanxi province's carbon reduction. In the SUS (sustainable) scenario, it assumes that the thermal power capacity will peak 85.78 GW in 2030 as the CPO and CPO_C scenario. After that it will keep the level of thermal power, develop renewable energy and accelerate the deployment of CCUS technology.

Table 1: Twenty aggregated sectors

No.	Sector	Abbreviation
01	Agriculture, forestry and fishery products and services	Agriculture
02	Coal mining and products	Coal mining
03	Oil and gas mining and products	Oil and gas mining
04	Non-metal and other mining products	Other mining
05	Food and tobacco products	Food and tobacco
06	Textile, leather, fur, feathers and their products	Textile
07	Wood processing products and furniture	Wood products
08	Paper products and cultural, educational, sports, entertainment supplies	Paper products
09	Refined petroleum and nuclear fuel processed products	Petroleum-nuclear fuel processed
10	Chemical products	Chemical
11	Non-metallic mineral products	Non-metal mineral products
12	Metal smelting and rolling processed products	Iron and steel
13	Metal products	Metal products
14	Equipment, instrumentation and manufactured products	Manufacture
15	Electricity and heat production and supply	Power
16	Gas production and supply	Town gas
17	Water production and supply	Water
18	Construction	Construction
19	Transportation, storage and postal	Transportation
20	Other services	Other services

Table 2: Additional cost for introducing CCUS technology.

Sector	Additional investment		Maintenance cost
High carbon concentration sector (Chemical)	1 % total	64 % in machinery 36 % in construction	8 % in electricity
Low carbon concentration sector (cement, steel, thermal)	25 % total	64 % in machinery 36 % in construction	10 % in electricity (cement and steel) 30 % in electricity (thermal)

Table 3: The deployment degree of CCUS technology in Shanxi province

Year	2025	2030	2035	2040	2045	2050	2055	2060
CCUS/%	1.2	3.2	9.5	19.5	39.8	49.6	81.8	97.3

3. Results and discussion

3.1 Carbon emission effects

The simulation results show that the coal phase-out and CCUS technology will certainly and significantly reduce the carbon emissions and Shanxi province can achieve carbon peak under different low carbon scenarios by 2031. The simulation results are shown in Figure 2.

Due to the high utilization of thermal power in BaU scenario, the carbon emission is expected to keep rising. While its carbon emission will peak in 2031 and reach 788.89 Mt under the CPO scenario, which reduce the

carbon emission by 11.58 % compared with BaU scenario. And with the coal phasing out and rapid decreasing from 2050, the emission is expected to decrease and reach 557.55 Mt in 2060, which is 617.38 Mt lower than BaU scenario.
With a deployment of CCUS technology, the emission is projected to reach a peak of 808.20 Mt in 2025 under the BaU_C scenario, which is even 29.94 Mt higher than BaU scenario. This is mainly because of the additional investment in electricity when introducing the CCUS technology. But with the diffusion of CCUS, in 2060, the emission will reduce by 58.87 % and reach 483.25 Mt.
When the coal phasing out and CCUS deployment happens together, under the CPO_C scenario, the carbon emission will peak in 2023 and reach 777.97 Mt. Then in 2060, the emission is projected to reach 393.58 Mt, which is 781.34 Mt lower than BaU scenario with a reduction by 66.50 %.

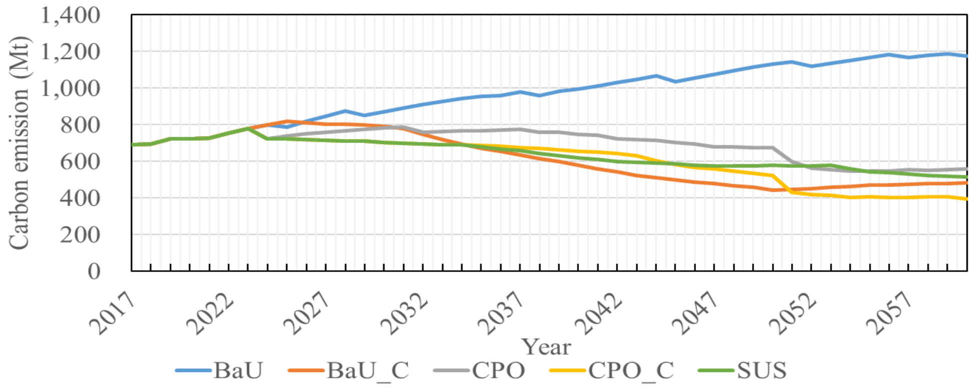

Figure 2: Carbon emissions in each scenario

3.2 Economic effect

As shown in Figure 3, under each low carbon scenario, the GDP will have a loss, compared with BaU scenario. With the deployment of CCUS technology and introduction of renewable energy, the cost of power generation will increase, which will have a negative impact on consumption.
Although the GDP has a loss of 38.42 %, 35.80 %, 36.24 % under BaU_C, CPO and CPO_C scenario respectively in 2060. It can be found that there is a certain increasing of GDP from 2035 to 2042 under the CPO_C scenario, compared with the BaU scenario, which will bring a largest economic benefit of 71.09 billion RMB in 2040.
When focus on the CPO and CPO_C scenario, it indicates that before the rapid decreasing of thermal power in 2050, the deployment of CCUS technology will keep mitigating the GDP loss from 2025. And in 2044, the CCUS technology may even have a 4.47 % increasing with 247.83 billion RMB.
The most significant GDP loss can be found in BaU_C scenario. It shows that when introduce CCUS technology from 2025 without any controlment in thermal power, the GDP will have a continuous and large loss than other scenarios.

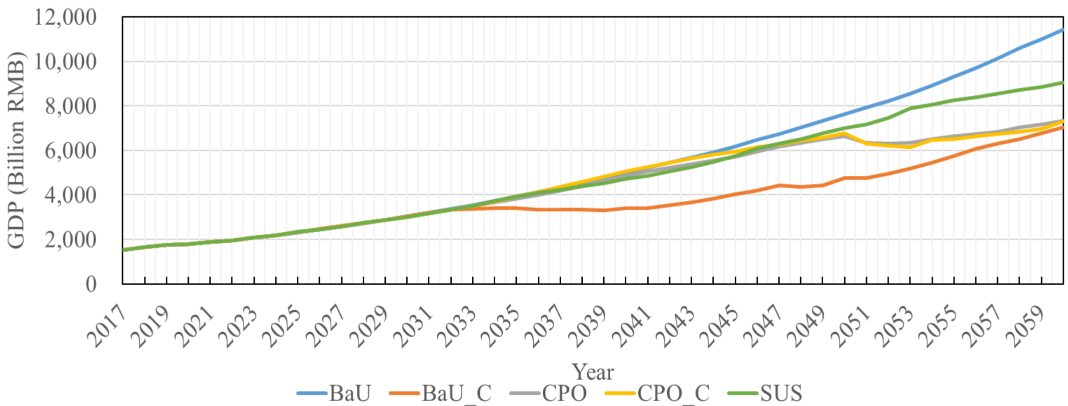

Figure 3: GDP (Constant price in 2017) in each scenario

3.3 Power sector

As it is shown in Figure 4, the total power generation will reach 917.16 TWh in 2060 under BaU scenario, while the power generation will decrease by 39.97 %, 40.07 %, 40.06 % under BaU_C, CPO and CPO_C scenario respectively.

In 2060, as set in CPO and CPO_C scenario, the thermal power will be eliminated, while the wind and solar power will be the main source of power generation with a share of 60.65 % and 35.87 %.

And it can be found that from 2030, the power generation in BaU_C scenario has been reducing until 2040. And the wind power and solar power have a development from 2030, which is different from the BaU scenario.

From the price of electricity, which is shown in Figure 5, it can explain why it has large GDP loss and decreasing in power generation in BaU_C scenario. With the high addition cost in CCUS technology deployment, the electricity price will increase from 2025 and have a rapid increasing from 2030. And due to the high thermal power share in power generation, with the same deployment degree of CCUS technology, it will have more CCUS investment than it in CPO_C scenario, which results in a larger loss in power generation and the development of renewable energy.

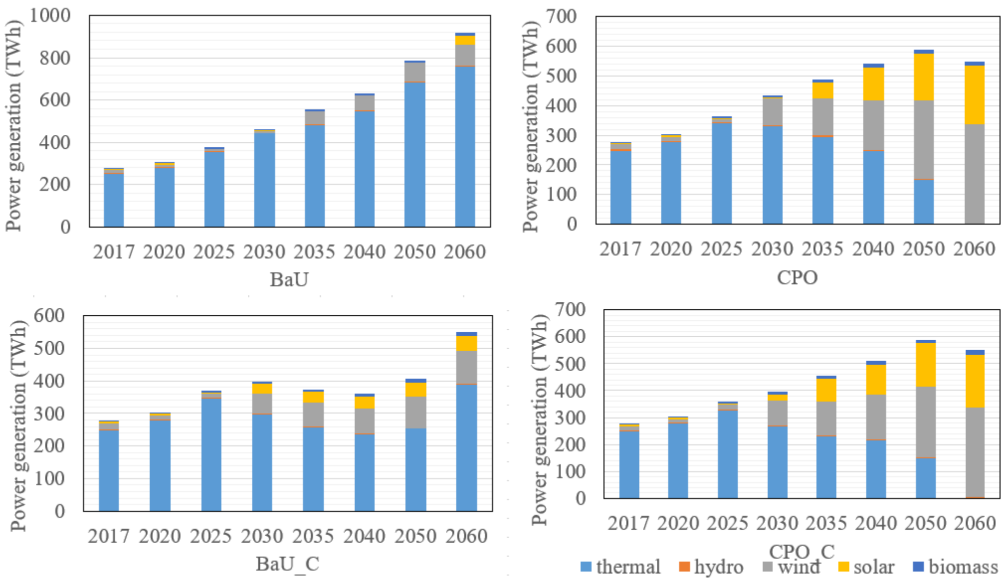

Figure 4: Power generation in each scenario

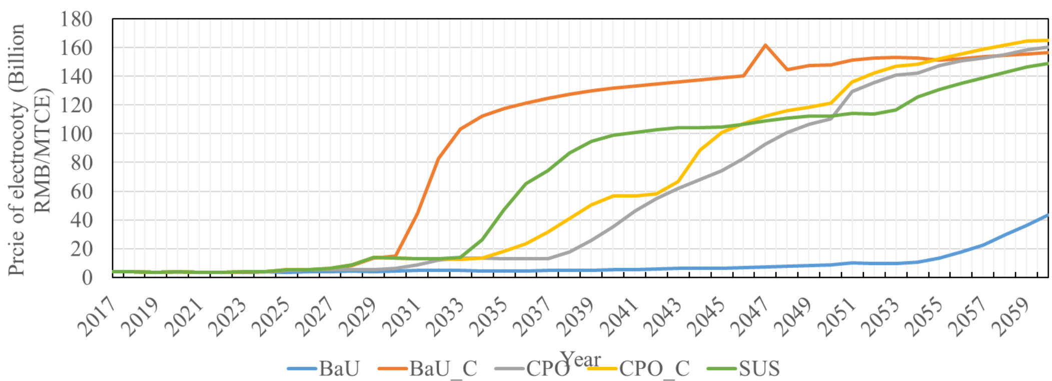

Figure 5: Relative price of electricity in each scenario

3.4 Discussion of sustainable pathway

Through the primary simulation results, it can be found that the CCUS technology can mitigate the economic impact when the power generation is transition from thermal power to renewable energy.

Compared to BaU scenario, under SUS scenario, in 2060, Shanxi province can achieve a 56.21 % carbon reduction with an emission of 456.06 Mt, while the GDP loss is 20.90 %. Its carbon cost in 2060 will be 3.62 kRMB/t, while the carbon cost is 6.35, 6.63, 5.30 kRMB/t in BaU_C, CPO and CPO_C scenarios.
And as shown in Figure 6, in the sustainable scenario, with the CCUS technology to accelerate the transition from thermal power to renewable energy in power sector, Shanxi province can keep a relatively lower carbon intensity level with 0.057 Mt per billion RMB to find a sustainable pathway.

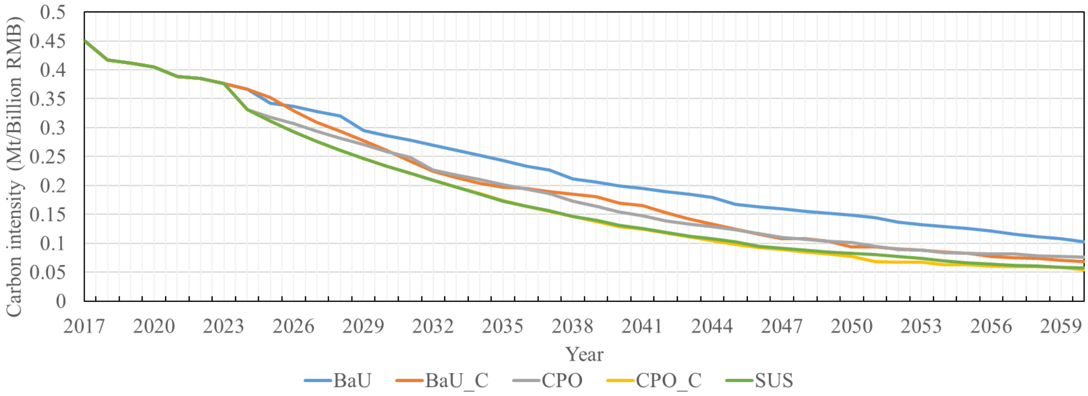

Figure 6: Carbon intensity in each scenario

4. Conclusions

To achieve carbon peak and carbon neutrality in Shanxi province, the coal phasing out and deployment of CCUS technology are the crucial measures. Through the construction of CGE model and scenarios simulation, there are several conclusions as followed:
As a coal-dependence province, its carbon emission and GDP are strongly related with the coal production and coal consumption. With the coal phasing out and high deployment of CCUS technology, it will significantly increase the social cost and seriously affect economic development.
Achieving carbon peak and carbon neutrality cannot rely on a single solution. The blind introduction of CCUS technology with a high cost may even seriously disrupt the balance of local market and damage the local economy.
Coal controlment in the short term with a long-term deployment of CCUS technology will be a sustainable pathway for Shanxi province to achiever the carbon reduction targets.

Acknowledgments

This work was supported by JST, the establishment of university fellowships towards the creation of science technology innovation, Grant Number JPMJFS2112.

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