Modeling for Energy and Economy Transition Using Multiple Objectives for China: The IPAC Analysis

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Abstract

Much research suggests that energy transitions have been driven mainly by CO_2 emission reduction targets. There are, however, other issues that could be included in assessing an energy transition in China. It would be possible to apply multiple objectives in assessing a transition. This paper presents ways to analyze energy transitions using multiple objectives with the Integrated Policy Assessment model for China (IPAC model). The use of multiple objectives of energy transition may be better for exploring factors influencing a transition, and provide a wider understanding of the energy transition by involving more stakeholders in the transition pathways. An energy transition towards a carbon-neutrality target would have the characteristics of clean energy, such as renewable and nuclear energy, dominating the energy mix, resulting in improved air quality and water demand control. Even though the use of carbon capture and storage (CCS) for fossil fuels may negatively impact energy for air pollutant control due to increased fossil fuel energy use, the amount of fossil fuel that can be used with CCS in energy transition pathways is also limited. Moreover, proper investments in energy transition could also benefit China's economic development. On the whole, adopting an energy transition pathway with a carbon-neutrality target in China could also support the realization of China's Sustainable Development Goals (SDGs) by 2030.

Key words: emission, energy transition, modeling, multiple objectives, scenario

1. Introduction

As of the beginning of 2022, more than 130 countries have announced a long-term target to be carbon neutral, or greenhouse gas (GHG) neutral by 2050, or before 2060. Energy transition plays a key role in the pathways toward achieving these carbon-neutrality targets (IPCC, 2022). As a low-carbon or zero-carbon energy transition is approached, renewable energy, especially solar PV and wind power, together with nuclear power are being developed rapidly now, and many countries have made their own plans and policies to enable an energy transition. The world is making moves to achieve the Paris Agreement targets (IEA, 2022).

Energy transitions, however, are linked not only with CO_2 emission reduction, though this may be the most important factor. Development of an energy system is a multi-dimensional decision-making process. The energy sector is one of the major industries in a country's economic system, and it is also the largest source of air pollutants in many developing countries. Among China's industrial sectors, the energy sector uses more water than any other. Energy suppliers are also the largest entity involved in mining, leading to issues such as land collapse, underground water disruption and water pollution (Bian et al., 2010).

Many studies have analyzed co-benefits between GHG mitigation and other environmental gains, such as air pollution reduction (IPCC, 2022; Qin et al., 2021). These studies normally analyze two environmental factors together without multiple objectives, and so far none have examined China's energy transition towards carbon neutrality targets closely.

The Integrated Policy Assessment for China (IPAC) modeling team started analyzing China's energy transition in the early 1990s, and was involved in both global studies and national studies. From 2016, their modeling analysis of an energy transition in China using IPAC started including several other objectives such as CO_2/GHGs mitigation, increasing the GDP, air pollutant reduction, decreasing water use, promoting a recycling economy and clean production (Jiang et al., 1998; Jiang et al., 2013; Jiang et al., 2018; Jiang et al., 2022; He et al., 2023a, b). This paper presents an analysis of an energy transition with these multiple objectives.

2. Methodology Framework

Energy transition pathways for China were analyzed using IPAC. The IPAC model was developed in collaboration with several leading modeling research institutes, including the National Institute for Environment Studies (NIES), Pacific Northwest National Laboratory (PNNL), International Institute of Applied System Analysis (IIASA), Netherlands Environmental Assessment Agency (PBL) and others. The IPAC model now includes several models with different modeling methodologies such as the IPAC-AIM/technology model, which is a bottom-up-type linear-programming cost-optimization model developed based on the AIM/end use model (Matsuoka et al, 1995); the IPAC-SGM model, which is a computable general equilibrium (CGE) model based on the Second Generation Model (SGM) model developed by PNNL (Hugh et al., 2005); and the IPAC-Global model, which is a partial equilibrium model of energy systems. To be an integrated assessment model, the IPAC model also includes a simplified climate model (MAGICC), and an air quality model based on AIM-Air. The IPAC Global model covers 11 regions, and has been used in several global wide studies (Jiang et al., 2006). The IPAC-SGM model has mainly been used for national studies, while the IPAC-AIM/technology model has been used for national and provincial studies in China.

A soft link was established among these models. The IPAC-Global model could provide parameters on global energy prices and energy imports and exports among regions, which could be used in other IPAC models; the IPAC-AIM/technology model could provide data on technological progress and energy efficiency improvements by sector; and the IPAC-SGM model could give parameters on energy prices, sector development and other conditions. The IPAC model uses scenario settings that are common among different models, so the parameters can be transferred among models, to maintain their consistency. By using the different characteristics of models in the IPAC model family, the output from IPAC could be interpreted with wider meaning. The IPAC-SGM model was used mainly to simulate the impact of mitigation on economic development and effects on fiscal policies such as carbon tax, subsidies. The IPAC-Global model was mainly used in the global analysis, with more of a focus on China (China by itself is one of the regions in the IPAC-Global model), and the IPAC-AIM/technology model was used mainly for energy transition pathways and the emission scenario analysis for China and selected provinces in China The model linkage is given in Fig. 1.

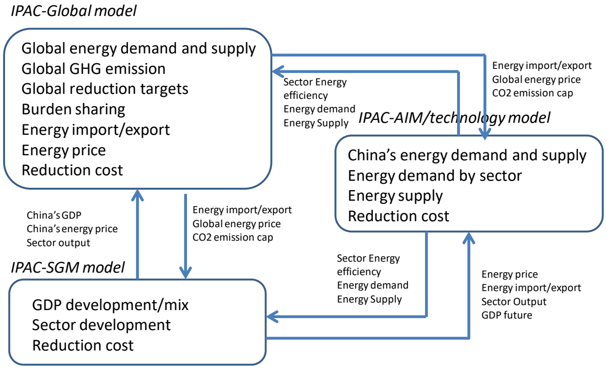

Fig. 1 Model flow chart.

An energy transition with multiple objectives was analyzed by using the model family to present different angles of these objectives.

To simulate air pollutant reduction, the IPAC-AIM/technology model was extended to cover some non-energy activities, such as air pollutant emissions from construction sites, agriculture activities and chemical industry activities. The sectors in the IPAC-AIM/technology model were extended from 55 to 61 to cover these non-energy activities, and more than 50 technologies were added in these non-energy sectors to reflect different technologies for air pollutant reduction.

3. Multiple Objectives and Scenario Design

The multiple objectives of the energy transition in China include carbon neutrality before 2060; air pollutant reduction to reach the World Health Organization (WHO) air quality standards by 2050; water demand reduction to secure water security issues in China, especially in northwestern China; and reduction of mining from the earth so as to protect the environment.

As for scenarios, one main scenario was used, with an energy transition in China driven by these multiple objectives. After China announced its target of carbon neutrality before 2060 in September 2020, to support the policy making process and related academic research, the research focus was shifted from a CO_2-mitigation scenario analysis to a wider analysis of the impact on energy transition pathways.

From 2000, IPAC modeling studies started working on air pollutant control based on energy activities. In China, energy sources account for around 65% of air pollutant emissions. From 2012, after the State Council released its clean air action plan, there has been much more research by the IPAC modeling team for analysis of air pollution control. The IPAC modeling team's main research topic now regarding air pollution control is an analysis of air quality improvement resulting from energy transition pathways toward the carbon-neutrality target. A zero-carbon energy transition could contribute well toward reaching air pollution control targets. One topic being discussed in China regarding air quality improvement is how to reach WHO standards by 2050.

Another key topic is water use reduction. In China, water scarcity is one of the key concerns in social economic development. With economic activities and household income increasing, water demand is also continuing to increase rapidly, and water pressure is becoming a serious problem in China (Xian et al., 2019). Several large construction projects have been carried out to transfer water from southern China to northern China. Water scarcity, however, continues to increase in China, especially in northwestern China. The energy sector is the largest water user among China’s industrial sectors. In 2020, the energy sector consumed 34 billion tons of water in China, second only to the largest user, the agriculture sector. Therefore, how to reduce water use in the energy sector is becoming one of the key issues toward an energy transition.

Another objective is to support economic development through the energy transition. A well-designed energy transition can be positive for economic development, even though most modeling analyses conclude that an energy transition with deep cuts in GHG pathways would have a negative impact on economic development (IPCC, 2022). It is important to figure out how to achieve positive support for economic development.

The next topic in our analysis of energy transition in China is how to support achievement of the Sustainable Development Goals (SDGs) in China by 2030. Many countries adopted the SDGs in 2015, and policy-making processes to support the effort to realize the SDGs are underway in those countries. In China, the government committed to achieving the SDGs by 2030, but it will face many challenges (Xue & Wong, 2019).

4. Modeling Output

4.1 Energy Transition

Figures 2 to 4 illustrate aspects of the energy transition scenario in which carbon neutrality is reached by the 2050 target, with hydrogen processes included in the model. Renewable energy power generation is estimated to reach 860 kcal/kWh, becoming the primary energy source, as in the International Energy Agency’s (IEA’s) model, which differs from that used in China, where a coal-fired power generation equivalent method is used.

The energy system will undergo a significant transition by 2050. By 2050, primary energy demand will decrease due to much more power generation and power available from renewable energy. Renewable energy and nuclear energy will account for more than 65% of primary energy. To achieve carbon neutrality by 2060, fossil fuel use will need to include use of carbon capture, utilization and storage (CCU&S).

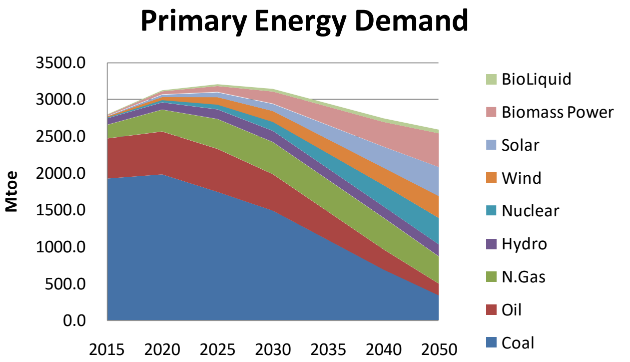

Fig. 2 Primary energy demand in the energy transition scenario.

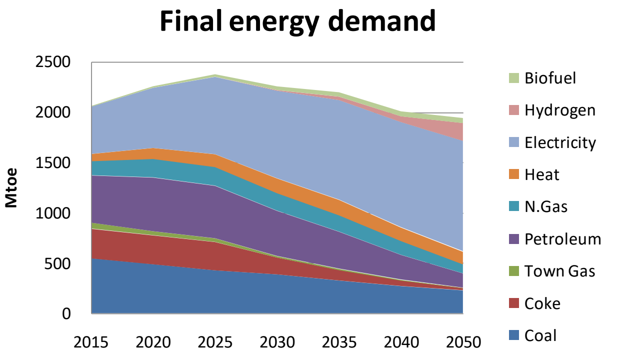

Fig. 3 Final energy demand in the energy transition scenario.

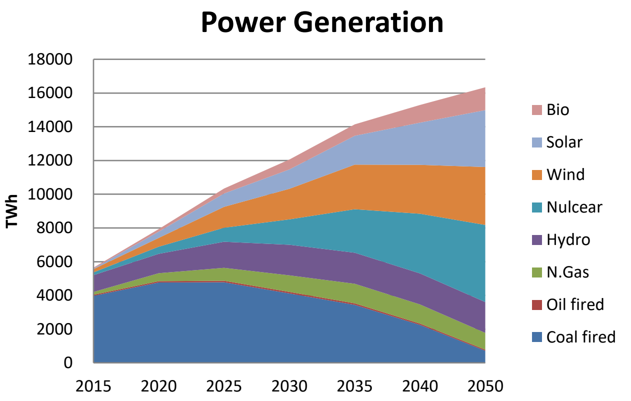

Fig. 4 Electric power generation in the energy transition scenario.

4.2 Air Pollutant Reduction and Air Quality

Because air quality is not a nationwide issue in China, the analysis of air pollution here is given by province. In 2013, the Action Plan on Air Quality Control (State Council, 2013) was announced, including a policy package, a major part of which focused on CO_2 emission reduction together with energy-related measures, such as controlling coal use and reducing the use of scattered coal, which have significant effects on air pollution.

Based on related studies, around 65% of air pollutants arise from energy activities. Therefore, an energy transition could result in significant air pollutant reduction. Shifting to a clean energy future will also result in lower air pollutant emissions. The objective of air quality analysis is to obtain the air quality standard recommended by the WHO, which was 10ŋg/m^3 before being revised to 5ŋg/m^3 in 2022).

Our air quality analysis using the IPAC model was performed by looking at 31 provinces rather than the nation overall, because air quality differed regionally. The socioeconomic scenarios of the 31 provinces were set up to include GDP, GDP by sector, population, number of households, output from sectors and other factors up to 2050 as driving forces for energy demand by province. Energy demand and supply were found by model simulation, and SO_2, NOx, PM2.5, VOC, black carbon and CH_4 emission estimates by province were obtained for up to 2050. An air quality model was used to calculate air quality by province. Table 1 presents the results for air quality by province.

It can be seen in Table 1 that it will still be difficult to reach the WHO air quality standard by 2050. The background air pollutant concentration is around 7−8 ŋg/m^3, and the emissions from the agriculture sector, where it is difficult to make deep reductions, could contribute another 3 to 4 ŋg/m^3. Therefore there is very big demand for air pollutant emission reduction from energy activities. To be able to reach the WHO air quality standard, air pollutant emissions from energy activities will have to be reduced nearly to zero. This may bring stronger demand for a clean energy transition than the carbon neutrality target by itself requires.

Table 1 Air quality, by province, ŋg/m^3.

	2015	2017	2020	2025	2030	2040	2050
Beijing	79.91	71.15	58.54	44.56	33.17	23.72	15.06
Tianjin	71.55	66.97	58.68	46.77	34.53	24.72	16.40
Hebei	76.74	68.57	57.18	44.50	34.59	22.01	15.91
Shanxi	55.80	49.59	37.74	29.68	22.98	18.24	14.36
Inner Mongolia	40.97	36.00	27.60	22.48	18.39	15.33	12.45
Liaoning	56.09	49.46	40.16	32.62	26.55	22.99	19.76
Jilin	56.26	46.41	36.07	28.32	23.18	19.84	16.55
Heilongjiang	44.70	35.78	28.47	22.74	19.47	17.12	14.77
Shanghai	54.03	48.58	40.19	32.52	26.47	22.32	18.19
Jiangsu	57.46	51.45	43.37	35.76	30.16	26.25	20.53
Zhejiang	47.93	42.87	34.80	26.95	20.83	16.82	12.78
Anhui	56.59	49.01	39.49	30.67	24.15	19.93	15.21
Fujian	28.92	25.75	19.89	15.34	11.91	10.04	8.56
Jiangxi	42.91	36.94	27.46	20.60	15.28	11.91	9.04
Shandong	68.13	60.72	48.38	37.67	28.92	23.50	18.76
Henan	80.96	71.01	55.59	42.88	33.25	26.12	20.31
Hubei	66.28	57.05	45.62	36.63	30.97	26.62	22.16
Hunan	53.46	45.10	33.98	26.33	20.42	16.70	13.40
Guangdong	33.81	30.21	23.61	18.06	13.79	11.31	9.47
Guangxi	40.55	34.84	26.73	19.45	13.90	10.54	8.13
Hainan	20.13	17.94	14.27	11.48	8.83	7.61	6.93
Chongqing	54.54	46.25	34.63	27.70	21.84	17.79	14.14
Sichuan	48.59	41.79	31.75	26.38	21.84	18.25	15.07
Guizhou	35.45	30.38	22.43	17.02	12.39	9.75	7.44
Yunnan	27.74	23.12	17.12	13.82	11.75	10.48	9.62
Tibet	26.43	26.30	26.00	25.82	25.82	25.87	25.95
Shannxi	54.02	47.32	38.94	32.55	27.88	23.50	18.85
Gansu	41.71	37.24	28.11	21.52	16.34	12.77	10.00
Qinghai	44.45	41.03	30.29	23.20	17.31	14.02	11.14
Ningxia	46.93	42.64	32.37	25.89	20.48	16.52	12.77
Xinjiang	55.56	53.34	43.84	36.49	28.44	22.37	15.87

4.3 Water Demand

Since the energy transition will have obvious impacts on water demand, understanding how water demand will be affected under specific climate change targets could improve support for energy transition policies in China. An energy-water integrated assessment model for China was constructed, based on an IPAC model framework. Water demand from the energy system was calculated based on China's energy transition pathways. The key influencing factors in water demand were analyzed for the energy transition scenarios. In the coming decades, the energy sector's water consumption will continue to increase, putting continuous pressure on water resources. Under energy transition scenarios, low-carbon energy technologies have different patterns of water use. Some mitigation measures increase water use in the energy sector, such as use of CCS and nuclear power generation.

The key influencing factors, including inland nuclear power, biomass energy, CCS and other water-intensive technologies, were identified. The results showed that water-saving measures could significantly reduce long-term water demand in the energy system, while short-term water stress in the energy sector is still inevitable. Meanwhile, as such water-saving measures decrease energy efficiency, it would be desirable to consider trade-offs between energy and water while making relevant energy policies and plans (He et al., 2023a).

Adjustment of the energy mix and the application of CCS technology result in differences in the amount and structure of water use in the energy system, as shown in Fig. 5. In the energy transition scenario, there is a very high demand for nuclear and biomass power generation. The rising water demand of these two technologies will lead to rapid growth of total water consumption, which will reach about 21.8 billion tons in 2030. That is an increase of about 7.4 billion tons, or 50.7%, from 2015. In addition, an energy transition will require rapid development and application of CCS technology, which will also lead to lower energy efficiency of power generation because around 30% of the energy is used to operate the CCS system, and greater water use is required by the technology itself. Therefore, under this scenario, water consumption in the energy sector will decrease briefly after 2030 to 20.3 billion tons in 2040, but rise again after 2040 to about 22.4 billion tons in 2050.

This means that transforming the power system may increase the pressure on regional water resources. In China, water resources are under great pressure, especially in inland regions, and power plants are already facing severe water shortages (Rosa et al., 2020). Therefore, for developing and siting new and planned

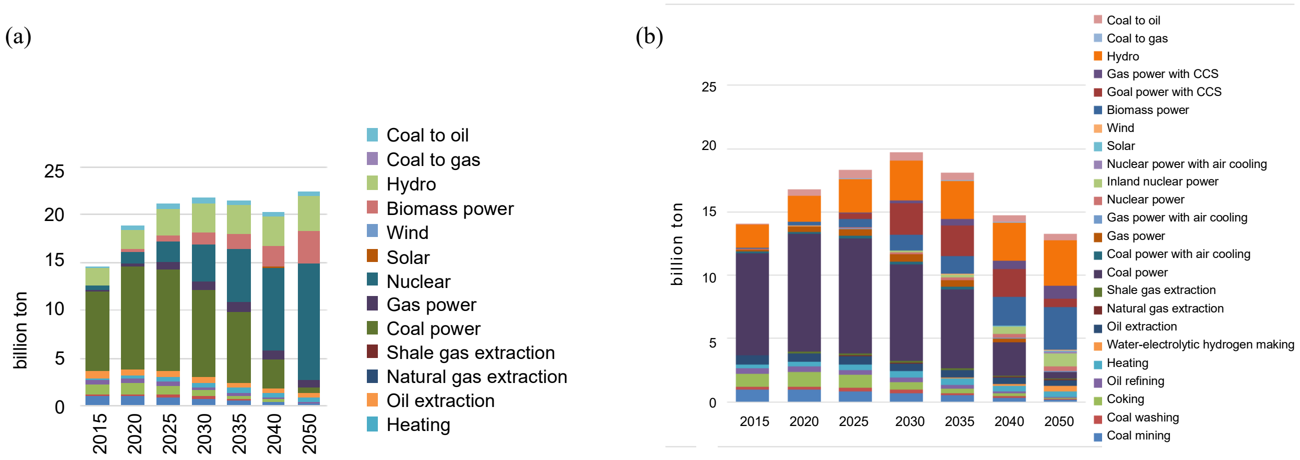

Fig. 5 Water consumption in energy transition scenarios in China. (a) Water demand in energy sectors without water saving technologies; (b) Water demand in energy sectors with water saving technologies.

power plants, especially inland nuclear, biomass and thermal power stations, it will be necessary to consider whether the regional water supply can meet the demand. In western and northern China, there are already serious water supply problems. Water scarcity needs to be taken into account in designing for different energy resource regions and consideration of power plant development planning and site selection. One advantage these western and northern regions have, though, is that they have tremendous solar and wind power resources, and developing solar and wind power uses much less water.

There are technological options for water conservation. The most prolific water user is nuclear power (Fig. 5a). If air-cooling technology could be applied, the water use in nuclear power plants could be reduced by 2/3. This technology is commonly used in China for coal fired power plants in regions with water supply pressure. Meanwhile, fourth generation nuclear power plants normally do not use water for cooling. In the IPAC energy transition scenarios, there will be around 560 GW of nuclear power by 2050, of which around 160GW will be fourth generation nuclear power. In the regions of China with water shortages, fourth generation plants or third generation plants with air cooling technology could be utilized. With water saving technology, water demand could be significantly reduced (Fig. 5b).

4.4 Impact on Economic Development

Based on our scenario analysis using the IPAC model, deep cuts to GHGs by 2050 in China, will influence economic development in the following ways:

- An energy transition will have an overall impact on economic development patterns. Clear reduction targets will require industries and consumers to respond. Policies aiming for reduction could impact the production system. There will be new industrial processes, including the use of hydrogen as feedstock and reduction materials for manufacturing industrial products, such as steel and chemical products; new technologies including advanced batteries for vehicles and power storage, advanced nuclear power generation and others; new materials which could replace high emission products, such as plastic made from renewable materials; new consumption behaviors including carbon labeling and carbon footprint lifecycle analysis, which would influence the manufacturing industry significantly; and new energy use patterns for achieving zero emissions, or even negative emissions from the energy supply. Due to GHG emission reduction, the whole economic system will have to undergo a transition to meet the requirements for deep cuts in GHGs.
- The energy supply industry will have to undergo a severe transition to a zero carbon energy system by 2050, and they will have to be highly secure with a totally new supply system. Together with the economic transition, there is a big potential for energy demand to increase with the zero-carbon energy supply. Moreover, many technologies will be needed for the energy supply transition.
- The end-use sector will also be impacted by the transition. Full electrification in the end-use sector, and new industrial processes with sharply reduced GHG emissions are key options for deep cuts in GHGs in China. Most transport, including airplanes, will use electricity or hydrogen from electrolytic processes. In industry, fossil fuels will be replaced by electricity, with 100% electricity use in buildings.
- New manufacturing processes will be developed in some sectors to make deep cuts in CO_2. This will be very important in the industrial sector where it is difficult to reduce CO_2 emissions in some processes, where we have to use fossil fuels as process inputs, such as in steel, cement clinker and chemical product manufacturing. Hydrogen could be an option for a reducing material, but there is a need for innovation of new processes. The good news is that hydrogen-based industrial processes are at a beginning stage, and there are several pilot projects underway.

Most studies find that mitigation of GHGs has a negative impact on economic development (IPCC, 2014; IPCC, 2018). Most point to big cost burdens imposed for mitigation to improve the environment, even though such cost benefit analyses of climate change abatement could include much larger benefits by examining the gains from the climate damage avoided. The negative impact on economies from GHG mitigation, however, has already attracted strident arguments from countries against moving further on mitigation, especially in the international collaboration process.

In traditional economies, prevention of air pollution and other environmental emissions could have negative impacts on economic activities (Jaffe et al., 1995). More recently, however, some studies have concluded that compatibility is possible between environmental improvement and economic development. Well-designed environment regulations could spark innovation from enterprises and subsequently improve their economic competitiveness. This is called the "Porter Hypothesis." This has not been fully supported by other studies, however.

China could make good policy choices for a positive impact on economic development through deep cuts in GHGs. Fig. 6 and Fig. 7 present our results from the IPAC-SGM model, which show that in energy transition scenarios, the GDP could be increased by 1.7% in 2050. Including linkage with the IPAC-AIM/technology model, the factors for an increased GDP include: 1) power generation costs being much lower with solar power and nuclear power generation, compared with baseline scenarios, due to more extensive development of solar PV and wind power, and the cost following the learning curve effects; 2) China's exports to other countries growing due to its gaining a lead in low-carbon technologies, with lower costs compared to elsewhere; 3) productivity also increasing due to technological innovation, and much lower costs for zero emission technologies, which could significantly reduce investment needs, and high efficiency in material use; 4) in the meantime, energy import expenditures being reduced through 100% locally supplied energy; and 5) greater energy conservation in the energy transition also lower energy expenditures by the public, resulting in higher consumption in other economic activities.

Recent studies focusing on economic impacts of air pollution control in China show there may be positive effects on economic development (Jiang et al., 2020). Such findings could encourage policy makers to consider their environmental improvement policies, and combine them well with economic development policies.

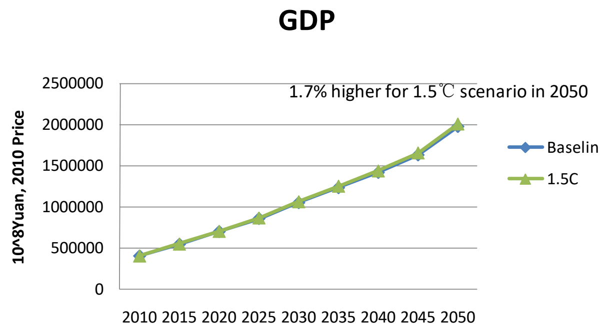

Fig. 6 GDP in the baseline scenario and energy transition scenario, IPAC results.

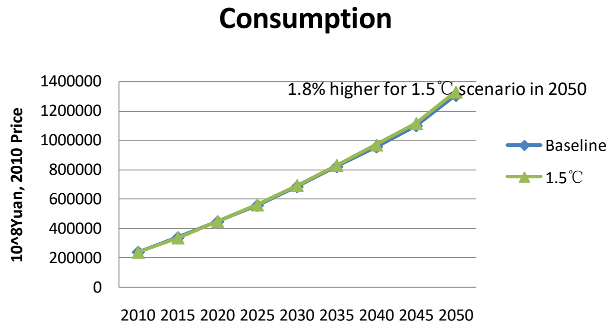

Fig. 7 Consumption in the baseline scenario and energy transition scenario, IPAC results.

4.5 The SDGs

The Sustainable Development Goals (SDGs) were also launched in 2015 during the Global Environment Summit. Agendas for reaching the SDGs were established by United Nations member countries. China similarly defined its national strategy for achieving the SDGs. The energy transition pathways towards the carbon neutrality target for China could have a close relationship with the SDGs, if ways the national strategy could contribute and overlap with achievement of the selected SGDs are explored. According to the results of studies on some of the SDGs, in conjunction with China's energy transition, pursuit of the SDGs may simultaneously lead to sustainable development in the energy, industry, transportation and building sectors, and thus improve environmental quality and human health. In addition to addressing climate change (SDG 13: take urgent action to combat climate change and its impacts), efforts to achieve the climate mitigation target will also produce co-benefits and facilitate the achievement of SDG3 (ensure healthy lives and promote well-being for all at all ages), SDG7 (ensure access to affordable, reliable, sustainable and modern energy for all), SDG8 (promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all), SDG9 (build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), SDG11 (make cities and human settlements inclusive, safe, resilient and sustainable), and SDG12 (ensure sustainable consumption and production patterns). The strong linkages between China's mitigation target strategy and the selected SDGs have implications for the necessity of merging the policies and actions relevant to climate mitigation and those relevant to SDG attainment, which could produce co-benefits and reduce policy costs.

The 17 SDG goals are further elaborated by 169 sub-targets, and can be quantified by the 241 indicators developed by the UN Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) (UN, 2016). Therefore, this research will link the energy transition scenarios with these SDG indicators to carry out a quantification analysis.

Since the framework of the IPAC-AIM/technology model uses a "resource-technology-service" flow, our study links the SDG indicators with the model following this flow: the clean and efficient use of energy and resources (linked with SDG7, SDG12) to generate environmentally-friendly growth and output (linked with SDG8, SDG9), resulting in sustainable cities ("green" lifestyles) (linked with SDG11). Within this system, other indirect indicators are also discussed, including environmental pollution (linked with SDG6) and health improvement (linked with SDG3) from using clean energy.

Quantified results for the 10 direct SDG indicators are given in this study, including SDG7: "ensure access to affordable, reliable, sustainable and modern energy for all," SDG8: "promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all," SDG9: "build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation," and SDG12: "ensure sustainable consumption and production patterns." The quantified indicators under the energy transition scenario are shown in Table 2 below (He et al., 2023b).

5. Findings and Discussion

Even though our energy transition analysis was mainly based on CO_2 emission reduction targets, there are many other issues that could be included in an energy transition assessment for China. This paper has presented ways to analyze an energy transition by using multiple objectives with the IPAC model. Having multiple objectives of energy transition could facilitate exploration of factors influencing the transition, and provide a broader understanding of the energy transition by involving more stakeholders in the transition pathways.

Based on this analysis, an energy transition towards a carbon neutrality target would be characterized by clean energy, such as renewable and nuclear energy, dominating the energy mix. The development of clean energy in China could also have a strong effect of reducing air pollution, possibly to nearly the air quality standard recommended by the WHO by 2050. Also, in general, an energy transition would also have positive effects on control of water demand. Even though there are some challenges regarding water demand for nuclear power, biomass power generation and CCS, which are water-consuming technologies, water-saving technologies exist for nuclear power generation. These technologies should be made available in regions with serious water supply constraints. Moreover, fourth generation nuclear technologies will not use water. By using these water-saving technologies, water demand could be reduced by 2050.

An energy transition would also impact future economic development. Many industries will undergo a significant transition by shifting to zero-carbon-emission manufacturing and new technologies; industrial processes will also undergo big changes; lower costs of clean energy will lead to less costly industrial manufacturing processes; and this then could result in changes in the allocation of industrial manufacturing in China by relocating industry from where it is currently concentrated in eastern China to western and northern China. Also, with lower energy

Table 2 Quantification of selected SDG indicators in the energy transition scenarios.

IAEG-SDG Indicators			Unit	2010	2015	2030
7.1.1	Proportion of population with access to electricity			-	100%	100%
7.1.2	Proportion of population with primary reliance on clean fuels and technology[1]			46.1%	52.7%	65.9%
7.2.1	Renewable energy share in the total final energy consumption[2]			6.9%	9.8%	21.9%
7.3.1	Energy intensity measured in terms of primary energy and GDP		toe/million US$ (2005)	501	387	185
8.1.1	Annual growth rate of real GDP per capita			17.7%	11.1%	6.2%
8.4.2	Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP[3]		ton/million US$ (2005)	638	523	135
			ton per capita	2.08	2.65	1.74
9.1.2	Passenger and freight volumes, by mode of transport	passenger-road	billion person km	3980	5339.5	10634
		passenger-railway		752	912	1385
		passenger-aviation		360.4	606.8	1841.9
		passenger-ship		7	7	7
		freight-road	billion ton km	3565	5209	10713
		freight-railway		2692	3347.5	5576
		freight-aviation		12	20.5	70
		freight-ship		7949	10122.5	18136
		freight-pipeline		209	430	1540
9.4.1	CO_2 emission per unit of value added		$kgCO_2$/US$ (2005)	1.92	1.23	0.44
12.2.2	Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP[4]		toe/million US$ (2005)	457	335	135
			toe per capita	1.49	1.69	1.74
12.5.1	National recycling rate, tons of material recycled[5]		million ton	-	1142.9	1314.4

[1] Natural gas penetration rate in households; [2] Including hydro, solar, wind and biomass; [3] Industrial material consumption, including iron and steel, cement, glass, copper, aluminum, lead and zinc, sodium, carbonate, caustic soda, paper and paperboard, chemical fertilizer, ethylene, ammonia, and calcium carbide; [4] Fossil fuel resources, including coal, natural gas and oil; [5] Recycling materials, including waste building materials, cement admixtures, glass, paper, plastic, copper, aluminum, lead, zinc and waste steel

costs resulting from the transition, zero-carbon-emission technology exports could increase, with costs for imported energy greatly reduced, and higher productivity due to technology innovation, the transition could also have a positive impact on economic development by increasing the GDP rather than reducing it, as many studies have shown.

There would still be some trade-offs in the transition among different objectives. The use of CCS for fossil fuels could have negative effects on energy for air pollutant control due to increased energy use, and it may also increase water demand. In energy transition pathways, the amount of fossil fuel that can be used with CCS is limited, and the total impact on air pollution control and water use is also limited.

On the whole, an energy transition pathway with a carbon neutrality target in China could also support the realization of the SDGs in China by 2030.

An energy transition could support different objectives, therefore the promotion of energy transition may be supported by different government agencies and organizations in China. Making an energy transition toward an energy system in which lean energy dominates is a multiple-win strategy in China, and should be strongly promoted now for the various benefits it would bring.

References

Bian, Z., Inyang, H.I., Daniels, J.L., Otto, F. and Struthers, S. (2010) Environmental issues from coal mining and their solutions. *Mining Science and Technology (China)*, 20(2): 215−223. Retrieved from graphic iopscience_header.jpg (accessed 4 October 2022)

He, C., Jiang, K. Liu, J. and Xu, X. (2023) Quantification of indicators for selected SDGs with the energy transition pathways for China, *Energy Economics*. (under review)

He, C., Jiang, K., Xiang, P. and Zhang, Y. (2023) Alignment of energy transition and water resources under the carbon neutrality target in China. *Journal of Integrative Environmental Sciences*. (under review)

IEA (2021) COP26 climate pledges could help limit global warming to 1.8 °C, but implementing them will be the key. Retrieved from https://www.iea.org/commentaries/cop26-climate-pledges-could-help-limit-global-warming-to-1-8-c-but-implementing-them-will-be-the-key (accessed 4 October 2022)

IPCC (2014) Fifth Assessment Report: Mitigation, Cambridge University Press, UK.

IPCC (2018) Special Report on 1.5°C Warming, IPCC report.

IPCC (2022) Sixth Assessment Report of WGIII: Mitigation, IPCC report.

Jaffe, A.B., Peterson, S.R., Portney, P.R. and Stavins, R.N. (1995) Environmental regulation and the competitiveness of U.S. manufacturing: what does the evidence tell us? *Journal of Economic Literature*, 33(1):132−163.

Jiang, K., Dai, C., He, C., Chen, S. and Xiang, P. (2020a) Impact of air pollution prevention on economic development in China after 2013: Case analysis for Beijing-Tianjin-Hebei, *Journal of CAS*.

Jiang, K., He, C., Dai. H., Liu, J. and Xu, X. (2018) Emission scenario analysis for China under the global 1.5℃ target. *Carbon Management*. https://doi.org/10.1080/17583004.2018.1477835

Jiang, K., Hu, X., Matsuoka, Y. and Morita, T. (1998) Energy technology changes and CO_2 emission scenarios in China. *Environment Economics and Policy Studies*, 1: 141−160.

Jiang, K., Hu, X. and Zhu, S. (2006) Multi-gas mitigation analysis by IPAC. *The Energy Journal, Special Issue*, 3: 425−440.

Jiang, K., Xing, Z., Ren, M. and He, C. (2013) China's role in attaining the Global 2 Target. *Climate Policy*, 13(S01): S55−S69. http://dx.doi.org/10.1080/14693062.2012.746070

Li, X., Shan, Y., Zhang, Z., Yang, L., Meng, J. and Guan, D. (2019) Quantity and quality of China's water from demand perspectives. *Environmental Research Letters*, 14: 124004. https://doi.org/10.1088/1748-9326/ab4e54

Lorenzo, R., Reimer, J.A., Went, M.S. and D'Odorico, P. (2020) Hydrological limits to carbon capture and storage. *Nature Sustainability*, 3(8):658−666. https://doi.org/10.1038/s41893-020-0532-7

Matsuoka, Y., Kainuma, M. and Morita, T. (1995) Scenario analysis of global warming using the Asian Pacific Integrated Model (AIM). *Energy Policy*, 23 (4/5), 357−371.

Pitcher, H.M, Sands, R.D. and Fawcett, A.A. (2005) The second generation model: Future directions for model development, October 2005. *PNNL Report*, Report number: PNNL-15437.

UN (2016) Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators. United Nations, New York.

Xue, L. and Wong, L. (2017) Opportunities and challenges for China to realize UN 2030 SDGs. *China Soft Science Magazine*, 2017(1): 12.

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