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RESEARCH ARTICLE

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Energy transition toward carbon-neutrality in China: Pathways, implications and uncertainties

Abstract Achieving carbon neutrality in China before 2060 requires a radical energy transition. To identify the possible transition pathways of China's energy system, this study presents a scenario-based assessment using the Low Emissions Analysis Platform (LEAP) model. China could peak the carbon dioxide (CO_2) emissions before 2030 with current policies, while carbon neutrality entails a reduction of 7.8 Gt CO_2 in emissions in 2060 and requires an energy system overhaul. The assessment of the relationship between the energy transition and energy return on investment (EROI) reveals that energy transition may decrease the EROI, which would trigger increased energy investment, energy demand, and emissions. Uncertainty analysis further shows that the slow renewable energy integration policies and carbon capture and storage (CCS) penetration pace could hinder the emission mitigation, and the possible fossil fuel shortage calls for a much rapid proliferation of wind and solar power. Results suggest a continuation of the current preferential policies for renewables and further research and development on deployment of CCS. The results also indicate the need for backup capacities to enhance the energy security during the transition.

Keywords carbon neutrality, energy transition, uncertainty, EROI, LEAP

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1 Introduction

Climate change is a profound challenge to humankind. To prevent climate disaster, over 190 countries have agreed to maintain the global temperature increase to below 2°C and pursue to limit the rise to 1.5°C (United Nations Framework Convention on Climate Change, 2015). Carbon neutrality in the middle of this century is essential to achieving this climate goal (Intergovernmental Panel on Climate Change (IPCC), 2018). As a responsible player, China has pledged to peak carbon emissions before 2030 and achieve carbon neutrality before 2060. This goal requires a dramatic reduction in carbon emissions, which may cumulatively reach 215 gigatons of CO_2 (Gt CO_2) from 2020 to 2060 (Pollitt, 2020). As 90% of carbon emissions originate from fuel combustion and industrial processes (International Energy Agency (IEA), 2021a), carbon neutrality largely relies on the decarbonization of the energy sector. Thus, a low-carbon energy transition is the core of China's climate target.

Energy transition refers to the transformation of the energy system from a fossil-based system toward a clean-energy-based system, mainly by scaling up renewables and improving energy efficiency (United Nations, 2021). Many countries have proposed energy transition roadmaps and implemented various measures to embark on this journey (IEA, 2021b), such as the *European Green Deal* by European Commission and the *Climate Change Act 2021* by Germany. China has also strongly promoted the energy transition. Renewables have recently dominated the capacity growth in China (China Electricity Council, 2021), and the energy intensity improved by 29% in the 2010s (State Council Information Office of China, 2021). Nevertheless, the present pace of energy transition in China is insufficient to realize the country's climate goals, and carbon neutrality calls for accelerated and intensive energy transition (IEA, 2021a).

Energy system transitions have been studied for a long time. Various pathways have been developed with varying carbon budgets and technological roadmaps. Examples include the global 1.5°C pathway (IPCC, 2018), 100% clean and renewable energy (Jacobson et al., 2017), and low energy demand pathway without carbon capture and storage (CCS) (Grubler et al., 2018). Focusing on China, a cross-model study revealed that over 90% of the total emissions of China should be mitigated to meet the 1.5°C goal (Duan et al., 2021). Following China's recent pledge on carbon neutrality, increased attention has been given to the energy transition toward net-zero emissions. A detailed roadmap for China toward carbon neutrality was issued by IEA (2021a), assessing the key technology needs, opportunities, and policy implications. Considering China's "new normal", a new growth pathway to carbon neutrality was proposed by Energy Foundation China (2020). Further to economy-wide studies, transition pathways have been investigated for key sectors, such as the transportation (Bu et al., 2021) and power (Chen et al., 2021) sectors.

While "gross energy" has been extensively studied, "net energy" provides a novel perspective on the transformation that is largely ignored in the literature. Net energy captures the difference between gross energy and the energy invested to energy production, which virtually fuels the economy (Carbajales-Dale et al., 2014). The energy return on investment (EROI) largely determines the net energy performance as it describes the ratio of gross energy to energy investment. Generally, energy transition commonly requires substitution between different types of energy. If energy resources with a high EROI are continually substituted by those with low EROI, the EROI for the entire energy system will decrease. Consequently, increased energy and economic activities will be required for energy production rather than running the economy, leading to decreased net energy supply and thus possibly disrupting the current lifestyles (King and van den Bergh, 2018). Relying on renewables with a low EROI may further result in a dilemma between meeting climate targets and avoiding energy shortages, i.e., the energy–emissions trap (Sers and Victor, 2018).

Uncertainty has been prevalent in energy transition. A range of factors, such as fossil fuel supply, renewable energy integration, and penetration of CCS, collectively determine an energy system. Therefore, the inherent risks present a challenge to the assessment of energy transition. First, the possible decline in the domestic production of fossil fuels (Wang et al., 2013) and the price fluctuation in the international fuel market (Alvarez, 2021) could increase the risk of supply shortages. Second, the preferential renewable integration policies that accelerated the expansion of renewables in China may not be sustained due to the high grid cost (Lin and Li, 2015), which decreases the benefit of renewables. Third, the deployment of CCS may be hindered by the high cost and difficulty of CO_2 utilization (Mac Dowell et al., 2017). These factors result in large uncertainties in the path and pace of energy transition and thus require further analysis.

This study adds to the literature by assessing the energy transition pathways of China with a focus on the net energy performance and the uncertainties in the transition. Specifically, in the first place, the EROI and net energy output variation in the energy transition and its implications on carbon neutral pathway are investigated. Secondly, the energy transition impacts of uncertainties in fossil fuel supply, renewable energy integration and CCS penetration are examined. To this end, this study explores possible pathways toward carbon neutrality in China and investigates the impacts of EROI variation and uncertainties. Two scenarios, namely, the business-as-usual and carbon neutral scenarios, are developed using the Low Emissions Analysis Platform (LEAP) model in which the sources of emissions mitigation are identified. The EROI variations during the energy transition are calculated, and their impacts on net energy performance, final energy demand, and carbon emissions are quantified. Moreover, three aspects that affect the emission reduction pathways or energy patterns are discussed. This study is expected to deepen the understanding of robustness and EROI implications for energy transition.

The remainder of this paper is organized as follows. Section 2 introduces the methodology, the assumptions, and the scenarios. Section 3 presents the results. Section 4 examines the impact of EROI, and Section 5 discusses the uncertainties. Section 6 concludes this paper with policy implications.

2 Methodology

2.1 Modelling framework

LEAP is an integrated and scenario-based tool for the accounting, simulation, and optimization of the energy system and has been widely used in energy transition roadmaps design (Stockholm Environment Institute, 2021). The flexibility and simplicity of LEAP allow the selection and setting of major variables of the energy transition, enabling the flexible exploration of any possibilities to reach carbon neutrality.

An accounting framework is proposed to investigate the carbon emission sources (Fig. 1), including an energy-related emissions module and a non-energy emissions module. The former is analyzed more deeply from the perspective of energy supply and demand. Only CO_2 emissions are quantified because they are the dominant greenhouse gas (GHG) emissions and largest contributor to global warming.

2.2 Scenarios setting

Two scenarios are developed in this study, namely, the business-as-usual scenario (BAU) and the carbon neutral scenario (CNS). Unlike some studies in which two or

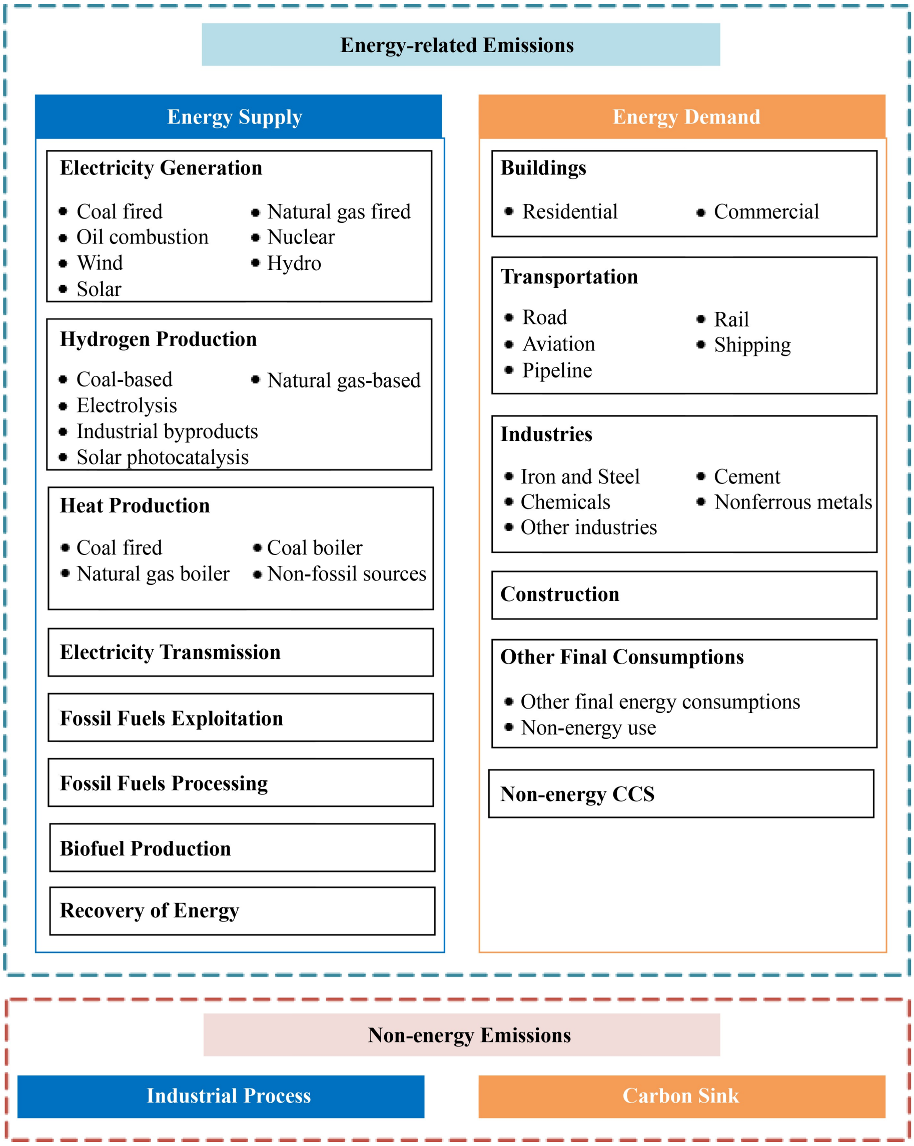


Fig. 1 Carbon emissions accounting framework.

more mitigation scenarios, which vary in alternative energy sources technologies (Luo et al., 2021), key technologies (Xiong et al., 2015), or carbon peak times (Zhang and Chen, 2021), were developed to assess different low-carbon transition pathways, only one scenario is designed in this study. This approach is taken because this study pays more attention to the net energy performance and uncertainties in the process rather than exploring other possibilities for energy transition toward carbon neutrality. Therefore, a possible pathway that covers most mitigation measures (i.e., CNS) could serve as a uniform basis for the thorough examination of these issues.

2.2.1 Key assumptions and general projections

The key assumptions and the general projections are shown in Tables 1 and 2, respectively.

2.2.2 Key measures for carbon neutral transition

As the baseline for comparison, BAU is set based on current policies and measures and thus follows the current trends of energy intensity and structure change. That is, low-carbon transition is underway but not rapid under BAU. Conversely, a rapid and radical energy transition to carbon neutrality is implemented under CNS, with five key measures (Table 3): Electrification and energy efficiency improvement (ELE), shift to bioenergy and hydrogen (BHY), non-fossil transformation of energy supply (NFT), decreasing demand for energy service (DEC), and deployment of CCS (DCCS).

2.3 Data

The data on socio–economic indicators, product and

Table 1 Key assumptions

Items	Assumptions
Base year	2018
Projected years	2019–2060
GHGs	Only anthropogenic CO_2 emissions from fossil fuel combustion, bioenergy combustion, and industrial processes are considered
Energy technologies	Most technologies are included, except for waste-based biofuels, synergetic fuels, and bioenergy with CCS
Electricity balance	All electricity generated is integrated well, and storage is ignored
Transmission loss	No loss is included, except for electricity
Input variables	Collective effects of transformation, such as activity level, energy intensity, and structure, are used
Carbon sink[a)]	Calculated based on the average amount of land carbon sink in China from 2009 to 2016[b)] and the projected growth of the Chinese forest stock[c)]

Notes: a) CO_2 absorbed by biomass cultivation is assumed to be involved in carbon sink, so the value used in this study is a conservative estimation result; b) Wang et al. (2020); c) Chinese Academy of Forestry (2021), National Forestry and Grassland Administration and National Development and Reform Commission (2021), National Forestry and Grassland Administration (2016).

Table 2 General projections

Parameters		2018[a)]	2030	2040	2050	2060
Population (billion persons)	BAU[b)]	13.95	14.50	14.49	14.02	13.33
	CNS[c)]	13.95	14.37	13.82	12.94	11.75
Urbanization rate[d)] (%)		59.58	70.00	75.00	80.00	80.00
Gross domestic product (GDP)[e)] (trillion yuan)[f)]		73.55	117.55	149.32	174.13	200.51
Carbon sink (Gt CO_2e)		1.11	1.25	1.35	1.45	1.50

Notes: a) All history data, except carbon sink, are from *China Statistical Yearbook 2020*; b) Projected values in BAU are calculated from *National Population Development Plan (2016–2030)* and *World Population Prospects 2019* "Medium Variant" by United Nations; c) The population of China has grown slower than expected in recent years and was projected to decline in the future (Dai et al., 2022); however, considering that the increasing income and high rate of technological progress would induce parents to raise fewer, higher-quality kids (Galor and Weil, 2000), this decline may be earlier and faster along with the progress in economy and technology in China. Thus, lower population was considered under CNS using the data from *World Population Prospects 2019* "Low Variant"; d) The data of 2030 are referred to *National Population Development Plan (2016–2030)*, which is assuming to be 80% in 2050 and keeping this level to 2060; e) Real GDP growth rate is collected from *Economic Outlook 103* by Organisation for Economic Co-operation and Development; f) Take the price in 2010 as the constant price.

Table 3 Key measures under CNS

Key measures	Related sectors	Scenarios	
		BAU	CNS
ELE	All demand sectors	The energy intensity decreases slightly, the share of electricity increases, and fossil fuels still dominates	The energy intensity decreases drastically; Electricity will be the major fuel, except in Cement, Chemicals, Aviation, and Shipping
BHY	Transportation: Road, Aviation, Shipping, and Pipeline Industries: Iron and Steel, Cement, Chemicals	Share of biofuel is negligible; Share of hydrogen is below 10% in 2060	In 2060, the share of biofuel and hydrogen in: Aviation and Shipping > 70%; Other sub-sectors except Rail > 20%
NFT	Electricity generation, Heat production, Oil and Gas exploitation	In 2060: Installed capacity of fossil fuel power plants = 1610 GW; Share of coal in heat production = 40%; Share of natural gas in heat production = 41%	In 2060: Installed capacity of fossil fuel power plants = 300 GW; Share of non-fossil heat sources = 47%; Less crude oil and natural gas will be produced
DEC	All demand sectors	Demand for products and service across all sectors changes following current trends	Population < values under BAU; Demands in all sectors[a)] < values under BAU
DCCS	Energy supply, Iron and Steel, Chemicals, Cement	No CCS will be deployed	In 2060, the penetration ratio of CCS in: Energy supply = 90%; Iron and Steel = 59%; Chemicals = 50%; Cement = 50%

Note: a) The demand for products and service across all sectors (i.e., energy service demand) is supposed to descend resulting from improved material efficiency, lifestyle transformation and less population (Grubler et al., 2018; Oshiro et al., 2021).

service demand, and energy intensity and structure for 2018 were collected from *China Statistical Yearbook 2020*, *Statistical Review of World Energy 2020* by British Petroleum, *Energy Balance* by IEA, and *China Electric Power Yearbook 2019*. The projections for the variables in the BAU were obtained by calculations through extrapolation and collected from other papers, such as *The Energy Transformation Scenarios* by Shell. Apart from above data sources, most data values for CNS were projected by referring to other multiply resources, including reports about energy transition or carbon-neutrality, sectorial transition roadmaps, specific technology reports, and scientific literature. Specifically, the main data sources and references of the five key measures under CNS are listed in Table 4.

3 Results

3.1 Energy supply and demand

The results of the future energy patterns under BAU and CNS show a drastic difference between scenarios (Fig. 2). Generally, the decline of the total primary energy supply under CNS is earlier and faster than that under BAU, and the proportion of renewables would be 3.4 times higher in 2060 under CNS. The total primary energy supply in 2060 under BAU (approximately 132 EJ) would be similar to that in 2018, whereas this value is nearly halved (70 EJ) under CNS. Regarding structure, renewables expand under each scenario but more significantly under CNS. Particularly, wind and solar energies will rapidly grow with annual rates of 5.6% and 6.5%, respectively. In 2060, renewables would become the predominant primary energy source under CNS (accounting for 71.1%), while fossil fuels would still account for well over 78% under BAU. However, the total fossil fuels supply would peak in 2030 (128 EJ) under BAU, and the rapid shift from coal to natural gas will advance the coal supply peak around 2025 (85 EJ).

Similar results could also be found for the final energy demand. The increased efficiency and accelerated electrification of the final energy demand under CNS contribute to the reduction of the total final energy demand, which will reach 67 EJ in 2060, 40% lower than the value under BAU. Under CNS, fossil fuels consumption will remain growing before 2030 but will decrease rapidly afterward. Instead, electricity, heat, and renewables would keep increasing and occupy more than 80% of the total energy demand in 2060.

Considering the gross domestic product (GDP) growth, the primary and final energy intensities would be improved significantly to 0.66 and 0.57 MJ/yuan, respectively, in 2060 under BAU, and these values are rather better under CNS (0.35 and 0.34 MJ/yuan) (Fig. 2(e)). Moreover, an evident amelioration of transformation efficiency from primary to final energy under each scenario could be implied, mainly because the replacement of fossil fuels by renewables in electricity generation reduces the primary energy consumption.

3.2 Carbon emissions

Benefitting from the non-fossil fuels' increase and energy efficiency improvements mentioned above, the total net carbon emissions of China would decline from 2018 to 2060 under both scenarios, but the mitigation pathway would greatly differ. Emissions would peak in 2025–2030 with a value of approximately 11.7 Gt CO_2 under BAU (Fig. 3(a)), which implies that China could peak carbon emissions before 2030 with current policies and measures. However, the emissions in 2060 is too high to meet the climate target. Thus, a tremendous mitigation in carbon emissions (7.8 Gt CO_2) is required to achieve carbon neutrality. Under BAU, industries and electricity generation will exhibit an evident reduction in emissions but will remain to be the two largest carbon sources from 2018 to 2060. However, under CNS (Fig. 3(b)), the industrial process sector will replace these two sectors to become the largest emission source with a share of 40.9% in 2060. The emissions from other sectors will decline even faster with a rate of over 80% under CNS. Regarding the contributions of different measures (Fig. 3(c)), ELE and NFT will be the major contributors, while the DCCS plays an essential role in realizing net-zero emissions, with 1.4 Gt CO_2 emissions predicted to be captured by CCS facilities in 2060.

3.3 Sectoral analysis

The contribution of each sector to carbon emission mitigation differs considerably (Fig. 4). Together, the

Table 4 Main data sources and references for variables under CNS

Key measures	Main data sources and references
ELE	Energy Transitions Commission: *China 2050: A Fully Developed Rich Zero-carbon Economy* State Grid Corporation of China: *China Energy & Electricity Outlook 2019* Global Energy Interconnection Development and Cooperation Organization: *Report on Carbon Neutrality in China before 2060*
BHY	IEA: *Energy Technology Perspective 2020* China Hydrogen Alliance: *White Paper on China Hydrogen and Fuel Cell Industry 2019* Fuel Cells and Hydrogen Joint Undertaking: *Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition*
NFT	Several energy transition outlooks respectively published by IEA, Economic and Technological Research Institute of China National Petroleum Corporation, Energy Information Administration, Institute of Energy Economics Japan, and DNV-GL Group in 2020 Shell: *The Energy Transformation Scenarios*
DEC	Energy Transitions Commission: *China 2050: A Fully Developed Rich Zero-carbon Economy* Corresponding data of European countries, like France Research articles, such as Grubler et al. (2018)
DCCS	Huabao Securities: *Report on Carbon Neutrality in Iron and Steel Industry* Boston Consulting Group: *Climate Plan for China*

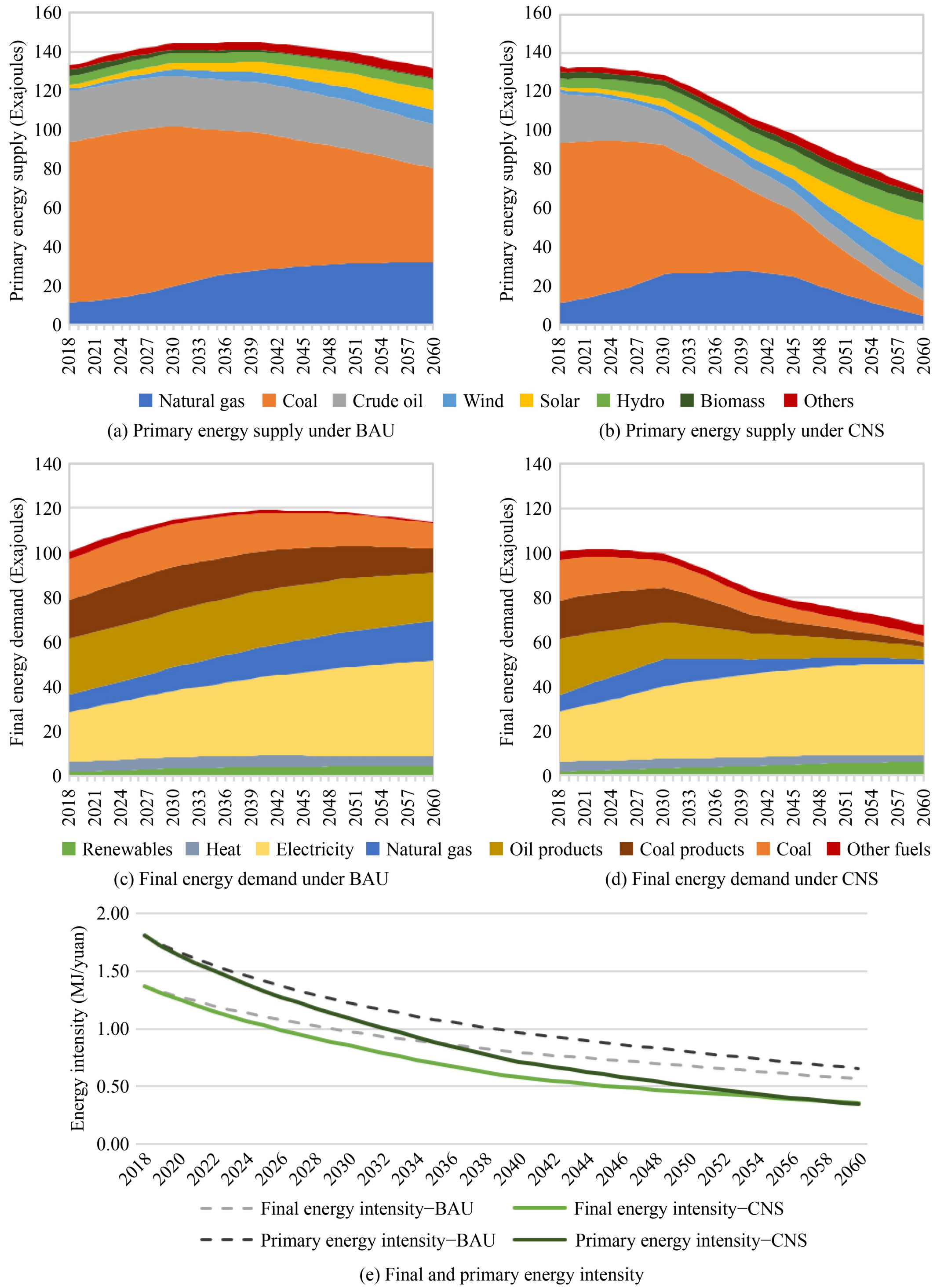


Fig. 2 Energy supply, demand, and intensity.

electricity generation and industries will be major contributors of carbon abatement. Notably, the emission mitigation in industries and industrial processes will decelerate after 2045, indicating the difficulty of further decarbonization in the industry sector. The energy and emission patterns for electricity generation and industries are discussed below.

3.3.1 Electricity generation

As shown in Fig. 5(a), the total emission in electricity generation will be mitigated by more than 99% in 2060 and reach practically zero. The emissions from coal-fired power plants will continuously decline, while those from natural-gas-fired power plants will increase before 2040

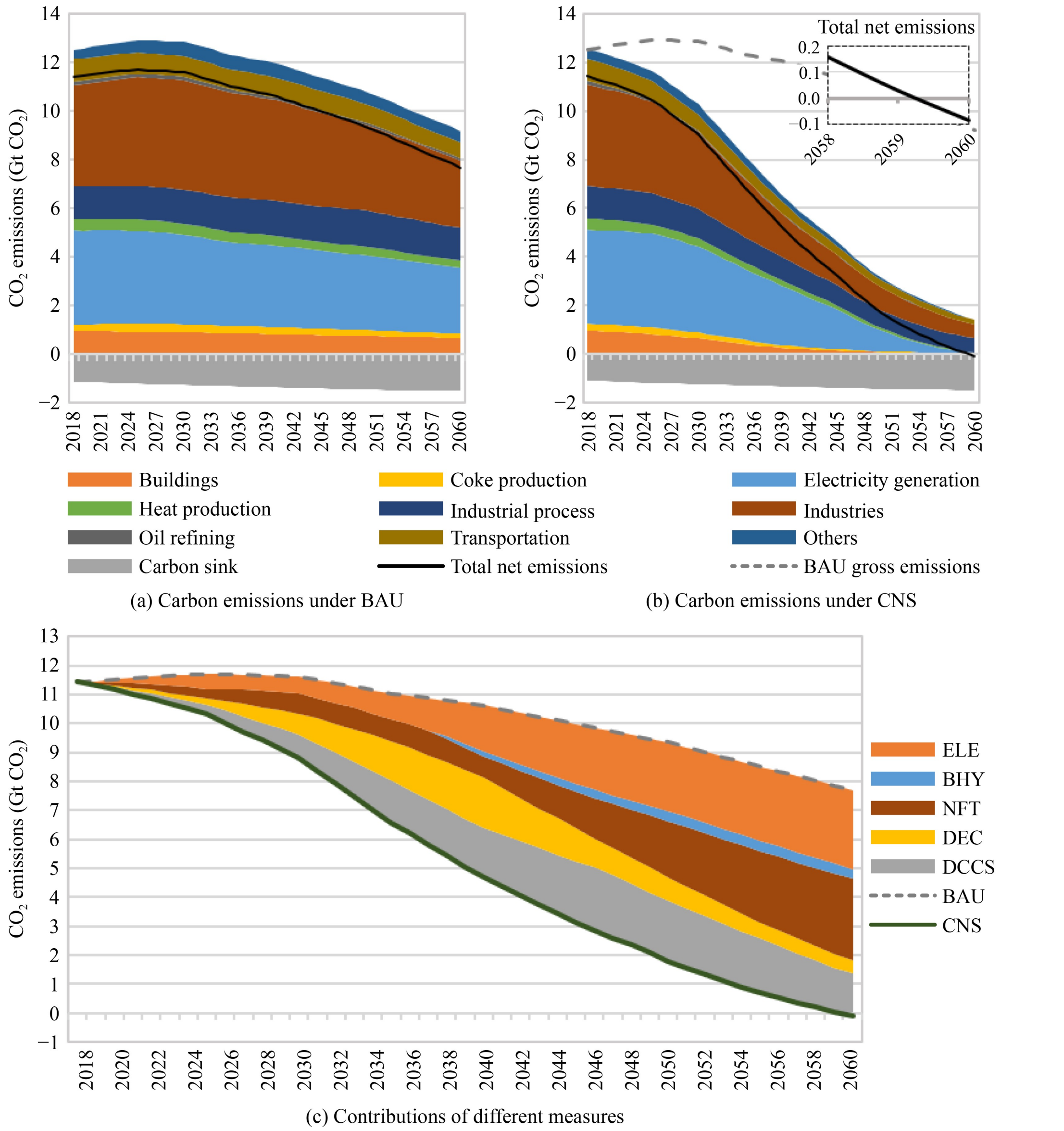


Fig. 3 Carbon emission mitigation under different scenarios.

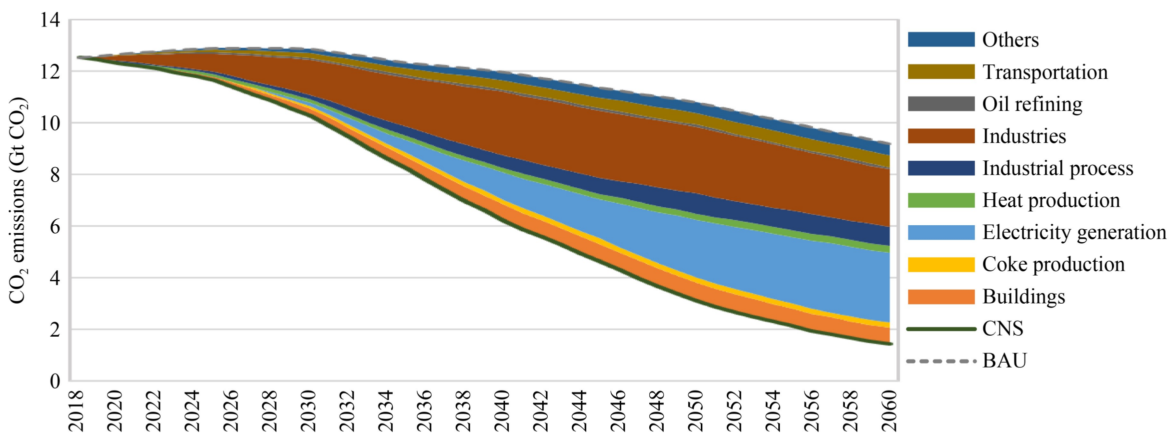


Fig. 4 Carbon mitigation contributions of different sectors without regard to carbon sink.

and drop afterward, which is in congruence with the transformation of the electricity output structure as illustrated by Fig. 5(b). The total electricity generation will nearly double in 2060 under each scenario, but the electricity generated by fossil fuels, especially coal, would decline more significantly under CNS than under BAU. Fossil fuel power plants will still play a vital role in electricity generation under BAU, but non-fossil power plants, especially solar and wind power plants, would proliferate rapidly and become dominant under CNS, with a total share of 96.3% in 2060. Under BAU, natural gas power will be the alternative for coal power, which will only be a temporal option under CNS before 2040 and soon be substituted by non-fossil power.

3.3.2 Industries

Figure 5(c) indicates that 2.22 Gt CO_2 energy-related emissions in industries will be avoided in 2060 under CNS compared with that under BAU. The emissions from the iron and steel sector will diminish with the highest rate (95%). Thus, this sector would no longer belong to the major emission sources in 2060 and be displaced by chemicals and cement. The emissions abatement is mainly driven by increased energy efficiency in demand and decreased consumption of fossil fuels (Fig. 5(d)). A total of 35 EJ of energy will be consumed by industries in 2060 under CNS, which is 1/3 less than that under BAU. As for fuel share, fossil fuels would still lead under BAU, but electricity, hydrogen, and biofuel would account for

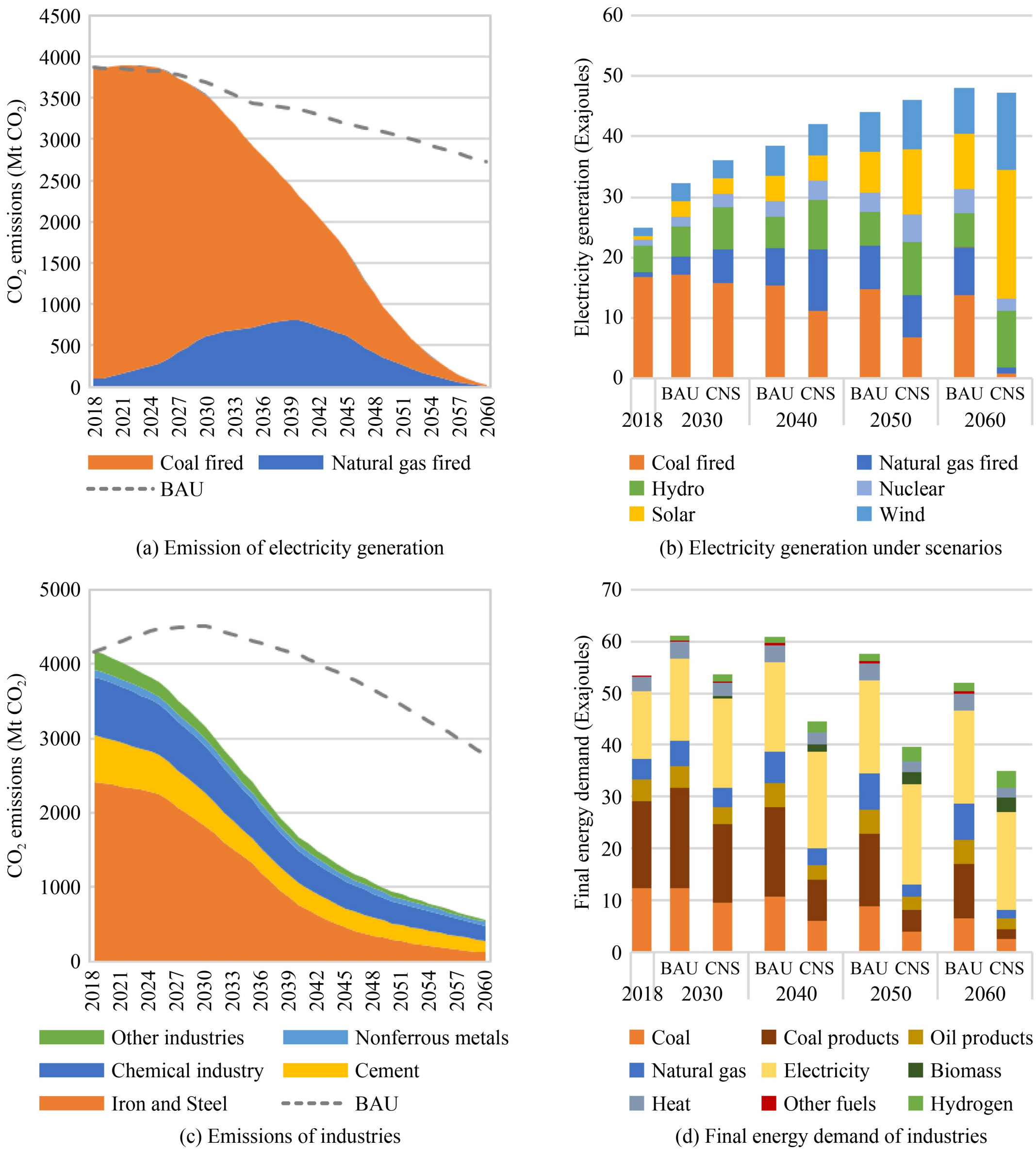


Fig. 5 Sectoral transition pathway.

the majority of the shares in industrial energy demand under CNS after 2040 and reach a total share of 71.5% in 2060. Moreover, the decreasing rate of fossil fuel reduction after 2040 could be a possible explanation for the decelerated emission mitigation in industries after 2040.

4 Implications of EROI for the energy transition

4.1 EROI and net energy output

EROI refers to the amount of energy yielded from each unit of energy invested to obtain it (Lambert et al., 2014). EROI represents the capability of the energy production process to provide "net energy output", namely, the energy surplus after deducting all the direct and indirect "energy investments" from the "gross energy output" as follows:

$$EROI = \frac{Energy\ delivered\ to\ society}{Energy\ invested\ to\ produce\ the\ delivered\ energy}, \quad (1)$$

$$E_{\text{net}} = E_{\text{gross}} - E_{\text{investment}} = E_{\text{gross}} \times \left(1 - \frac{1}{EROI}\right), \quad (2)$$

where E_{net} denotes the net energy output, E_{gross} signifies the gross energy output, and $E_{\text{investment}}$ is the energy investment.

The equations show that the proportion of net energy will diminish as the EROI declines. For example, to produce 1 petajoule (PJ) of oil, switching the production from conventional oil source (*EROI* = 18) to tar sands (*EROI* = 4) will mean that the net energy output of oil for arbitrary use will drop from 0.94 to 0.75 PJ; and switching to coal-to-liquid technology (*EROI* = 0.9) (Kong et al., 2019) will cause a negative net energy output, that is, all produced oil will be used by the process itself, and an additional 0.11 PJ is needed from the external processes.

In other words, a lower EROI implies a higher energy investment with the same gross energy supply. This investment not only includes the direct fuel burnt to power the process but also the energy consumed to produce the material and equipment for constituting the energy supply facilities, such as the electricity consumed for photovoltaic (PV) module fabrication. Consequently, this investment will be included in the final demand. However, the energy supply in LEAP is optimized based on the gross energy balance in which the final energy demand is exogenous. That is, the additional energy investment derived from the EROI decline would not be captured in the capacity expansion and dispatch, and the energy supply will be insufficient. Therefore, the EROI variation and net energy supply in the process of energy transition are considered in this section.

4.2 Net energy supply of China under energy transition

According to the existing literature, different energy carriers have drastically different EROIs (Table 5), so the transformation of the energy structure may change the EROI of the total primary energy supply (system EROI). Considering the uncertainties in the EROI for each energy (individual EROI), uncertain results are obtained using Monte Carlo analysis (Fig. 6(a)). An evident downtrend for the system EROI could be found under each scenario, which is more prominent under CNS than under BAU despite the uncertainty. The difference may result from the fact that more energy carriers with higher EROI (such as coal) are replaced by those with lower EROI (such as solar) under CNS.

Table 5 EROI of different energy carriers

Primary energy	*EROI*			Reference
	Min	Mean	Max	
Coal	26	31	35	Hu et al. (2013a)
Indigenous oil	8	10	14	Hu et al. (2013a); Cheng et al. (2018)
Indigenous natural gas	8	10	14	Hu et al. (2013a); Cheng et al. (2018)
Biomass	8	12	24	Wang et al. (2021a)
Hydro	38	57	73	Hu et al. (2013b); Zhang and Pang (2015); Li et al. (2017)
Wind	11	21	29	Chen et al. (2011); Yang and Chen (2013); Huang et al. (2017); Feng et al. (2020)
Solar	3.4	7.0	13.6	Lu and Yang (2010); Nishimura et al. (2010); Yue et al. (2014); Cao et al. (2016); Liu and van den Bergh (2020)
Geothermal	20	40	60	Chang et al. (2017); Liu (2017)
Nuclear	11	14	17	Hall et al. (2014)
Imported oil	4	7	14	Kong et al. (2016)
Imported natural gas	8	14	16	Kong et al. (2016; 2018)

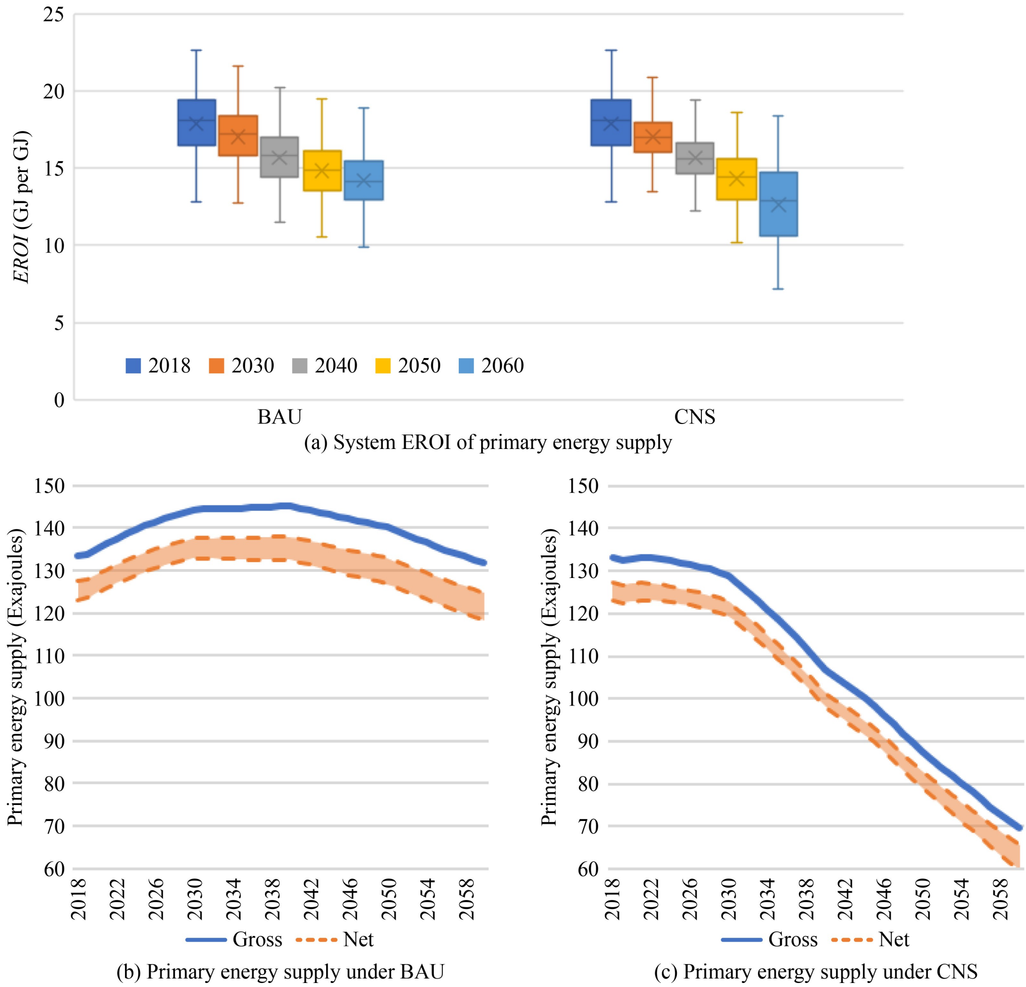


Fig. 6 EROI and net energy supply variation under energy transition.

In terms of energy supply, a widening gap between the gross and net energy supplies could be observed in Figs. 6(b) and 6(c). This phenomenon indicates a more intensive drop in net energy supply than in gross energy supply and the increasing trend of the share of energy investment, implying that the actual final energy demand will be higher than projected because the original value is projected with the assumption that the share of energy investment is constant (invariable EROI). Thus, the energy supply derived from the original demand will be lower than the actual demand, which will lead to energy supply insufficiency. Lower planned energy supply makes this problem worse under CNS.

4.3 Alternative option to capture the extra energy investment under CNS

To capture the extra energy investment, the interaction between energy supply and demand was developed in some studies using system dynamics (Dale et al., 2012; Sers and Victor, 2018). Inspired by those studies, this study adds an extra energy investment to the gross final energy to draw more energy supply. Referring to Capellán-Pérez et al. (2019), an EROI feedback factor is adopted to modify the projected final energy demand with its original value and system EROI as follows:

$$D(t) = D^0(t) \times FC_{\mathrm{EROI}}(t) = D^0(t) \times \left(\frac{EROI(t)}{EROI(t)-1} \times \frac{EROI(t_0)-1}{EROI(t_0)} \right), \quad (3)$$

where $D(t)$ and $D^0(t)$ respectively denote the modified and original forecasting results of the gross final energy demand in year t, $EROI(t)$ and $EROI(t_0)$ respectively represent the system EROIs in year t and the base year t_0, and $FC_{\mathrm{EROI}}(t)$ is the EROI feedback factor in year t.

By distributing the modified total final energy demand to each fuel on the basis of the original energy structure, EROI variations are involved in the pathway design for energy transition toward carbon neutrality. The result (Fig. 7) shows a higher amount of final energy demand than planned in most cases when the EROI variation is considered. Moreover, the extra energy demand will keep increasing in the majority of cases, reaching 6500 PJ in

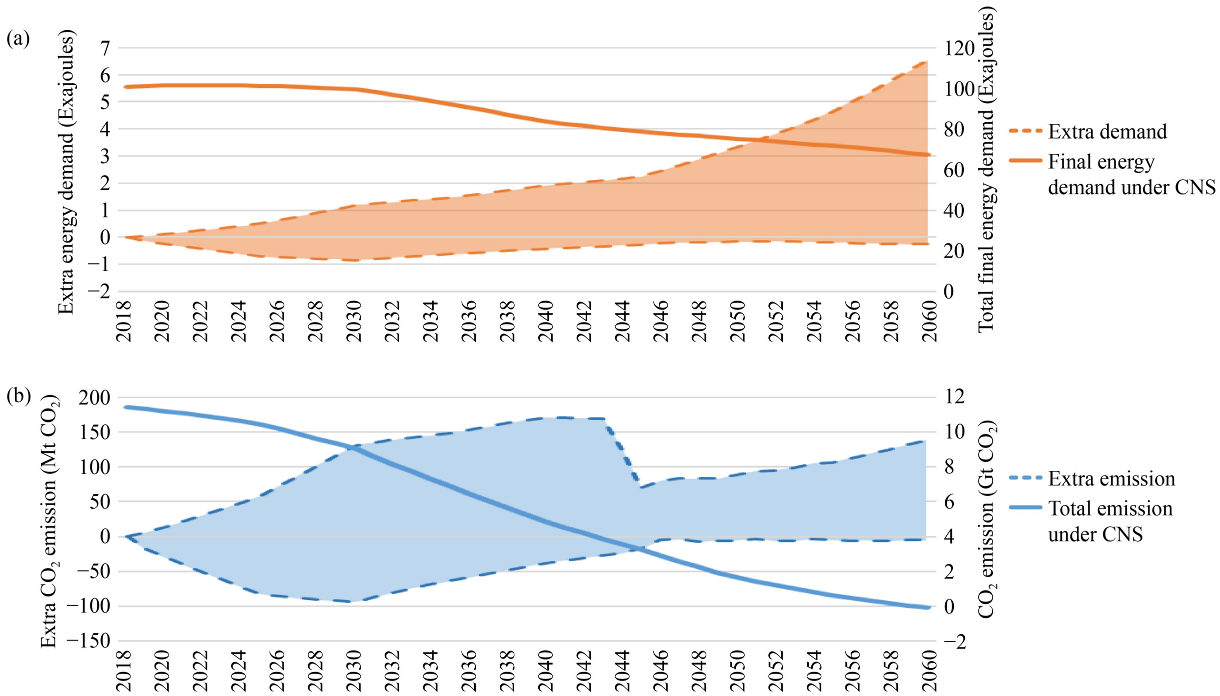


Fig. 7 Impact of EROI variation on (a) energy demand and (b) carbon emissions.

2060 under the worst scenarios. Regarding emissions, meeting the extra energy demand will likely increase the emissions and may even result in failure in realizing carbon neutrality in 2060 (increased 138 megatons of CO_2 (Mt CO_2)), making the energy transition step into the "energy–emissions trap". However, the data from 2040 to 2045 shows that the extra emissions will drop in many cases. A possible reason is that in these years, the installation of more solar and wind capacities will be provoked by the increased peak power demand, increasing the share of renewables of electricity generation under preferential renewable integration policies (Section 5.2). A possible implication is that more renewables should be tapped to simultaneously offset the extra energy demand and reduce the carbon emissions, thereby preventing the energy and emissions dilemma stemmed from the EROI decline.

Nevertheless, the uncertainty of individual EROI may cause a quite different result under some scenarios. For example, the largest difference in extra energy demand between the best and worst cases is approximately 6800 PJ, and the extra emissions may be negative in some years under optimistic scenarios. Actually, the results of EROI estimation will be affected by the research boundaries and the caliber of energy statistics. To reduce these uncertainties, the individual EROI values are adjusted using the "standard EROI" boundary coined by Murphy et al. (2011), and the thermal equivalents of each energy source are adopted for energy accounting. However, the EROI calculation could also be affected by other factors, such as energy quality and production sites, requiring more attention to acquire a reliable and robust EROI estimation result.

5 Uncertainty analysis

To assess the instability of energy transition, further uncertainties related to fossil fuel supply, renewable energy integration, and penetration of CCS are discussed in this section.

5.1 Fossil fuel supply

From the technological perspective, non-fossil energy sources are abundant in China and sufficient to meet the energy demand under CNS (Table 6). Nonetheless, an appropriate growth rate of non-fossil energy capacity is necessary to ensure the energy security in the pace of fossil fuel withdrawal. However, in the energy transition process, fossil fuels may not be always available, which will accelerate the fossil fuel withdraw and thus require the installation of increased non-fossil energy capacity. This deficiency of fossil fuels stems from two factors. First, physical restraints would increase the difficulty of obtaining cheap fossil fuels and even cause depletion in the future, especially in China where oil and gas resources are limited. Second, price fluctuations may decrease the affordability of fossil fuels. For instance, the power rationing in some provinces of China in 2021 was mainly caused by the soaring coal price. To investigate the influence of possible fossil fuels deficiency, a new

Table 6 Potential and demand values in 2060 of main non-fossil energy sources in China (unit: EJ/year)

Non-fossil energy sources		Potential[a]	Energy demand
Solar	Centralized	4.67–23.33[b]	22.67
	Distributed	> 1.58	
Wind		27.52–88.92	12.70
Hydro		8.91–21.90	9.37
Biomass		57.53–101.24	4.57

Notes: a) The data of distributed solar potential refers to Wang et al. (2021b), and others are from Liu et al. (2011); b) The potential is estimated by only using 1%–5% of desert area to install solar power, so the result is conservative and could be higher in the future.

scenario called low fossil fuels (LFF) is established based on CNS, decreasing the use of fossil-based technologies in electricity generation, heat production, and hydrogen production and filling the gap by renewables and electricity after 2025.

Figure 8 indicates a noteworthy reduction in carbon emissions under LFF compared to CNS, especially from 2025 to 2050. Nonetheless, this reduction is to a great extent at the expense of an evident increase in electricity requirement and the early and accelerated proliferation of the wind and solar power capacity. Specifically, the average annual growth of the wind and solar power capacity before 2045 under LFF is 34.5% higher than that under CNS. This result appears to support the recommendation that additional wind and solar power should be deployed as backups for possible fossil fuel shortage.

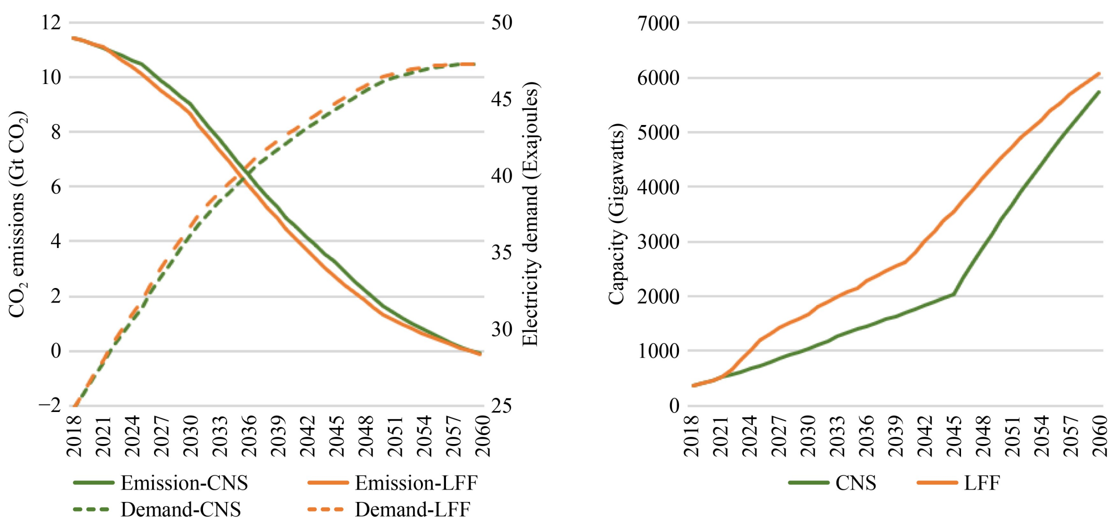
5.2 Renewable energy integration

In this study, electricity generation is dispatched endogenously among technologies on the basis of the dispatch order and capacity. Current policies for renewable energy integration assume that wind, solar, and hydro power will be first dispatched. However, the high penetration of intermittent renewables retards their full integration. Thus, the current preferential renewable integration policies may not be sustained. To examine the impact of possible changes in policy, two new scenarios are presented, assuming that solar, wind, and hydro power will no longer be dispatched first (CIP) and even dispatched after fossil-fired power (NPIP) for the possibly high cost of integrating intermittent energies.

The difference among scenarios (Fig. 9) suggests a noteworthy increase in carbon emissions with the change in integration policies, especially in the near future. Furthermore, the level of cumulative carbon emission is likely to increase by 8–23 Gt CO_2, leading to a high temperature increase. The additional emissions are mainly from electricity generation and will be 1.8–2.4 times higher in 2060, implying that the change in preferential renewable integration policies would hamper the climate benefit of renewables, notably in the power sector.

5.3 Penetration of CCS

Achieving carbon neutrality before 2060 requires the construction of adequate CCS facilities for removing excess emissions. However, affected by the substantial investment and difficult storage and utilization of CO_2 (Mac Dowell et al., 2017), the deployment of CCS may not develop as planned. To explore this uncertainty, scenarios CCSD5, CCSS5, CCSD10, and CCSS10 are introduced. In these scenarios, the annual CCS penetration ratio under CNS will decelerate (accelerate) by up to 5–10 years, respectively. Figure 10 shows a distinct dissimilarity among the different deployment pathways of CCS, signifying that delaying the deployment of CCS



(a) Emissions and electricity demand
(b) Total capacity of wind and solar

Fig. 8 Impact of short supply of fossil fuels.

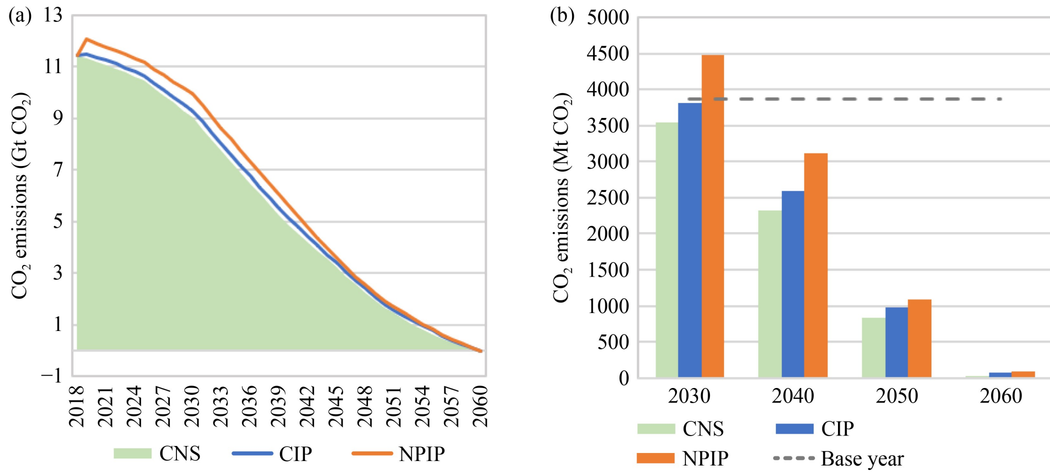


Fig. 9 Impact of changed integration policy on emissions of (a) whole system and (b) electricity generation.

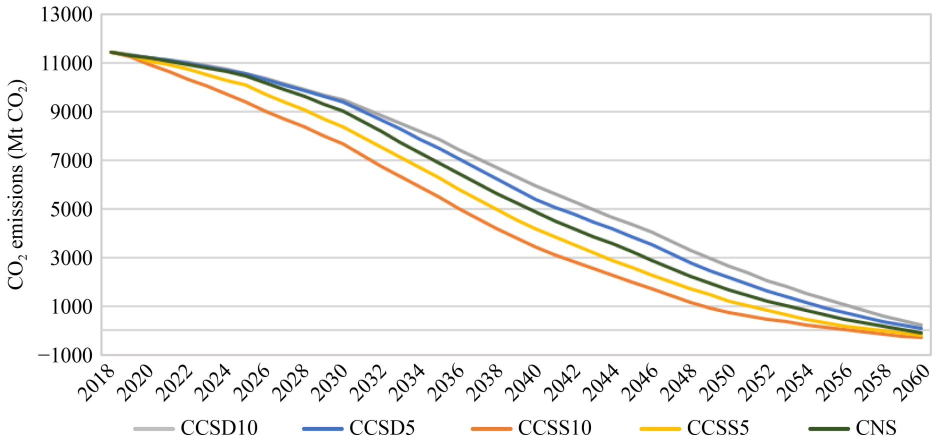


Fig. 10 Carbon emissions under different CCS penetration ratios.

from 5 to 10 years (CCSD5 and CCSD10) will probably increase the total emissions by 158 to 318 Mt CO_2. Moreover, carbon neutrality will be realized earlier under CCSS5 and CCSS10 than under the other scenarios, and it could not be realized by 2060 under CCSD5 and CCSD10. This finding suggests that the realization of carbon neutrality in China would depend on the extent to which CCS could work. Therefore, treating CCS as the "silver bullet" for energy transition would be dangerous unless additional research & development and incentives for CCS are performed.

6 Conclusions

This paper explores possible pathways for energy transition toward carbon neutrality in China and investigates the impacts of EROI variations and uncertainties. China could peak CO_2 emissions before 2030 with current policies in place, while achieving carbon neutrality in 2060 requires an extra reduction of 7.8 Gt CO_2 in emissions. Effective measures include electrification, phase-out of fossil fuels, efficiency improvements, and use of CCS. Of the major sectors, industries and the electricity sector would be the primary contributors. System EROI and the net energy output are likely to decline under the energy transition, leading to energy shortage. Filling this gap would increase the final energy demand and thus lead to additional emissions. Moreover, fossil fuel supply insufficiencies are found to likely increase the renewable energy demand, the alternation of the current renewable integration policies might decrease the emission mitigation effect of solar and wind power, and the uncertain deployment of CCS would hamper the carbon neutrality.

Some policy implications can be drawn from the findings. First, the scale of wind and solar power should be massively increased. The results show that the declining EROI and the uncertain fossil fuel supply may lead to imbalances, which must be properly assessed. To ensure energy security, clean energy might have to be increased more rapidly than commonly assumed to provide adequate energy supply. Second, promotion of renewable energy integration and CCS deployment should be prioritized. Renewable policies could enhance the climate benefit in the near future, and CCS is vital for deep decarbonization in the long run. Considering the challenge in large-scale renewable integration and CCS scale-up, more efforts should be put into these options. Third, it is critical to consider thoroughly the developments of EROI during the energy transition in policymaking. Our results indicate that improperly considering the EROI variation may mislead energy supply necessities in the energy transition and its consequences for meeting emission targets. To consider this potential risk, the variation of EROI and its impact on energy transition pathway requires further investigation.

This study has some limitations. In particular, the approach adopted only provides one possible energy transition pathway under a set of exogenous variables rather than an optimal pathway. Further study could look deeper into the role of technology innovation and economy–energy–environment interactions for the purpose of drawing more complete transition roadmaps. In addition, the EROI is changing with technological developments, and these dynamics of EROI are ignored, which is another direction that deserves further investigation.

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