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Scenario analysis of carbon emission trajectory on energy system transition model: A case study of Sichuan Province

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ABSTRACT

Energy transition targets and pathway planning are more important since the declare of carbon peak and carbon neutrality in China. Energy transition is highly relevant with economic and social development, as well as industrial transformation and technological innovation. However, existing studies have rarely conducted energy transition and CO_2 emissions analysis from the macro targets of economic development and climate change as well as micro pathway of different sectors. In this study, we propose an energy transition framework to present an energy transition mechanism driven by various impact factors. First, a sectional energy consumption module is presented to analyse energy consumption transition linking economic development, technology progress, and low-carbon policy effect. Then, the energy conversion and supply module is proposed, tracing back energy flows from demand to supply to provide an overview of the energy transition. Subsequently, empirical scenario analysis of Sichuan Province is conducted, followed by whole perspective and targets of energy transition as well as CO_2 emission mitigation trajectory. The results indicate that: (1) Sichuan's Carbon peak and carbon neutrality will be achieved in 2028 and 2058 under the Energy Transition Scenario; (2) Clean electrification transition would result in an insufficient renewable power supply for outer-region demand from 2030 to 2050, and Sichuan Province would not be able to meet its carbon peak and carbon neutrality goals if natural gas is added to generate more electricity to ensure the export volume; (3) Energy efficiency improvement, energy mix optimization and the increase of penetration of renewable power can reduce CO_2 emission by 13.3 Mt, 87.8 Mt, and 5.4 Mt in 2050 in Energy Transition Scenario. The model extends the modelling methodology of energy-economy-environment system and provides an effective scenario analysis and path selection tool, which can provide a scientific and quantitative reference basis for policy makers in the context of energy regulation and energy network governance and can be applied to the study of energy transition paths in other regions.

1. Introduction

As people pay more and more attention to climate change, many developed countries have announced timeline for carbon peak and carbon neutrality in response to climate change. For instance, the UK Climate Change Act 2008 [1] and the Japanese Plan for Global Warming Countermeasures [2] have clarified the goal of achieving carbon neutrality by 2050 proposed by the government in the form of legislation. The main measures of carbon emission mitigation include the development of low-carbon energy, adjustment of energy consumption structure, optimization of industrial structure, energy conservation and efficiency, increase of carbon sink and low-carbon life, etc. [3–7]. The ultimate goal is to promote economic prosperity and sustainable development [8]. As a developing country, China is still in the stage of rapid urbanisation, motorization and industrialization, and will still consume more energy in the future development process. Hence, China's emission reduction path formulation not only confronts the challenge of energy replacement of existing stock, but also faces the problem of energy consumption increment caused by development requirements [9,10]. China needs to reach a peak phase before it can move to net zero emissions. In September 2020, China declared that it would

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Abbreviations

AAM	Average Annual Mileage
BAU	Business as Usual
BS	Building Sector
CE	Carbon Emission
CT	Commercial Transportation
DCE	Direct Carbon Emissions
EC	Energy Consumption
EF	Carbon Emission Factor
EI	Energy Intensity
EM	Energy Mix
ET	Energy Transition
ETAM	Energy Transition Analysis Model
EEU	Energy End-Use
Ex	Export
FEC	Fossil Energy Consumption
FES	Fossil Energy Supply
FS	Floor Space
HE	Heat Generation Efficiency
HEU	Heat End-Use
HGM	Heat Generation Mix
ICE	Indirect Carbon Emissions
Im	Import
IS	Industrial Structure
LNG	Liquefied Natural Gas
LP	Local Production
N	Number
NG	Natural Gas
O	Oxidation Ratio
OI	Opening Inventory
P	Population
PEU	Power End-Use
PGE	Power Generation Efficiency
PGM	Power Generation Mix
PS	Production Sector
PV	Private Vehicle
R	Change Rate
RA	Residential Area
REP	Renewable Energy Production
RES	Renewable Energy Supply
TS	Transportation Sector
TT	Traffic Turnover
U	Urbanisation
VP	Vehicle Population

strive to carbon peak by 2030 and achieve carbon neutrality by 2060.

Energy-related CO_2 emission is the main source of China's carbon emissions [11]. According to Carbon Emission Accounts & Datasets [12, 13], in 2019, China's energy consumption was 4.9 gigaton of standard coal equivalent (Gtce), with fossil energy consumption contributing to 92.2% of the total energy consumption. It resulted in energy-related carbon dioxide emissions as high as 9.8 Gt, accounting for 85% of China's total CO_2 emissions. In this regard, it is the main measure to achieve total CO_2 emission reduction by energy system transformation. Energy system transformation aims to transform the energy system based on high carbon content fossil energy such as coal and oil into low carbon energy involving electricity and hydrogen generated by renewable energy [14,15].

According to the current regional carbon emission accounting method of the Ministry of Ecology and Environment of the People's Republic of China, carbon emissions not only come from the burning of fossil fuels but also from purchased electricity. Consequently, energy-related CO_2 emissions should be considered from both a consumption perspective as well as electricity production. In terms of energy consumption, the transformation of energy consumption structure involves coal to electricity, oil to electricity, etc [16,17]. From 1996 to 2016, the contribution of energy consumption structure to inhibiting CO_2 emissions is slight [18], but China could realise large amount of carbon emission reduction by accelerating electrification and maximizing the use of renewable energy technologies [19]. However, the transformation of energy consumption structure may face the pressure of marginal abatement cost and welfare loss in the short term [20]. In addition, energy conversion technological progress has an inverted U-shaped relationship with CO_2 emissions [21]. In terms of energy supply, a significant increase in the proportion of renewable energy in the power supply sector is an important process to achieve carbon neutrality [22]. In response, through incentive policies and technology push [23–25], China's renewable energy power generation industry, such as photovoltaic [26], has achieved unprecedented development. Sichuan province, with unique advantages in hydropower, wind power and other clean energy resources, has attracted more attention [27]. Luo et al. found that by setting three energy supply routes of electricity, biomass and natural gas, Sichuan Province can reduce CO_2 emissions by 91.52%, 90.48%, and 58.17% in 2050, respectively [28]. However, Suo et al. predicted that due to the limitation of renewable energy resources, fossil fuels will still account for 61.09% of the total energy supply even in 2050 corresponding to the increasing demand for energy due to the rapid economic development [29]. Considering the life cycle analysis, the CO_2 emissions implied by imported or exported electricity will also affect regional CO_2 emissions [30], that is, the indirect CO_2 emission implied by electricity and heat consumption [31], especially in the case of large-scale power transmission across regions [32]. Therefore, to achieve the goal of carbon peak and carbon neutrality, increasing electrification level on the energy consumption stage and increasing the proportion of renewable energy on the energy supply stage are important directions of CO_2 reduction. An earlier peak gives China more time to arrange for the orderly phasing out of coal-fired power and the steady deployment of renewable energy. While there may be greater transition pressure in the near term [33]. At present, an important issue facing many regions in China is how to guarantee sufficient renewable energy to ensure energy supply while ensuring the improvement of electrification level. This not only affects the energy security for regional economic development, but also influences the trend of CO_2 emissions.

Most of the recently applied models take energy, environment and economy into consideration when discussing energy transition pathways and provide valuable insights to the strategies in achieving carbon peak and carbon neutrality targets [33–44]. However, there are still some drawbacks of traditional energy transition models: 1) some traditional energy transition models [34,35] focus on the isolated stages of energy consumption or supply, and cannot simultaneously evaluate the carbon emission reduction effect by involving energy consumption, energy supply, energy conversion and energy transfer. 2) Some models focus on the linkage of energy transition and economic development while the bottom-up technologies are roughly categorized [36,37]. 3) some models focused on the specific subsectors or technologies rather than analysing the entire system transitions [38–40]. 4) Some other studies [41,42] put forward a framework for socio-technological energy transition to cover both energy supply and demand, while they mostly focused on the energy system transformation framework and did not conduct linkage analysis on the carbon emission trajectory [48,49]. Therefore, it is necessary to provide a methodology for regions to present comprehensive energy transition target and pathway achieving economic development goals as well as meeting CO_2 emission mitigating constraints.

In summary, existing studies have rarely conducted energy transition and CO_2 emissions analysis from the macro targets of economic development and climate change as well as micro pathway of different sectors. This study aims to propose an energy transition approach combined the methods of top-down and bottom-up to present an energy transition mechanism driven by various impact factors and posed energy flows transition tracing back from demand to supply which could explore regional carbon reduction pathways. With energy consumption module, the model adopted in this study links energy transition with regional economic and social development. With energy conversion and supply module, the model enables energy supply-demand balance with consideration of technological improvement and sectoral transformation. With carbon emission module, the model evaluates the direct and indirect carbon emission in energy transition pathways. In this way, this study makes up for the drawbacks of existing research from the aspects of macro-micro combination and energy supply-demand balance and provides valuable insights for regional energy transition pathway design and analysis.

The contribution of our work lies in two aspects. From the theoretical aspect, the energy transition model we present extends the modelling methodology of energy-economy-environment system model, and realizes the unification of top-down macro model and bottom-up technology model in the level of energy supply and demand balance. In terms of application, the model in this paper provides an effective scenario analysis and path selection tool, which can provide a scientific and quantitative reference basis for policy makers in the context of energy regulation and energy network governance and can be applied to the study of energy transition paths in other regions.

2. Methodology

2.1. Modelling framework

In this paper, the authors conduct a systematic analysis of the energy transition (ET) under the target of carbon peak and carbon neutrality. Different from bottom-up methods that categorise the final energy demand into specific sectors, the method this paper adopts combined the bottom-up method and top-down method that focuses on systematic transition in terms of energy consumption, conversion, and supply. The energy consumption in production sector, building sector and transportation sector is included in the end-use sectors. As for the accounting scope of regional carbon emissions, this study adopts the scope 2 of carbon emissions, which not only considers the direct carbon dioxide emissions from local energy consumption but also the indirect carbon dioxide emissions generated by purchased electricity [45]. Therefore, we further analysed the indirect carbon emissions caused by power supply under the energy transition of terminal consumption.

2.1.1. Energy system transition analysis

Energy transition involves the energy supply, consumption and conversion stages and relates to coal, oil, gas, and renewable energies. Under the premise of guaranteeing economic development and individuals' living needs, energy transition includes energy efficiency improvements, low-carbon energy mix adjustment and renewable power penetration rate. Energy transition analysis model (ETAM) is analysed through several internal influencing factors contributing to the change of energy and external factors (Fig. 1). The internal factors refer to the energy exploitation and production, energy consumption, energy conversion, and energy transmission and distribution. The external factors refers to economic development plan and the target of carbon peak and carbon neutrality which will affect the four internal factors. The four internal factors interact with each other and the whole energy flows. In the process of energy transition, energy substitution policy, technology innovations and energy efficiency not only impact energy consumption mix and quantity but also energy conversation and even energy exploitation and production. In addition, the share of renewable power will significantly influence carbon emissions which depends on electricity supply mix. The transition in the sub-systems of energy supply, energy conversion, end-use, and development plans for energy and the economy will reshape the energy flows and structure. Finally, the energy transition analysis model is solved using the 'LINPROG' equation solver in Matlab.

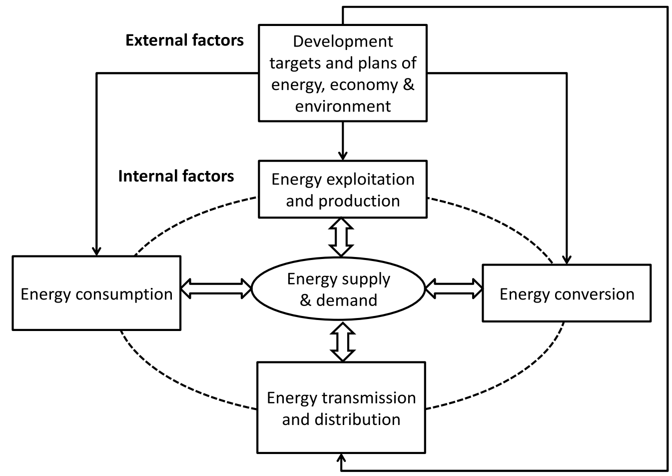

Fig. 1. Framework of energy system transition.

The main influencing factors of an energy system are further explained as follows:

(1) Energy exploitation and production: Energy exploitation and production refers to the potential of coal, oil, gas, wind, solar and hydro resources available for exploitation in the region. In addition to ensuring the security of energy supply, increasing renewable energy power will also have an important impact on the total carbon emissions of the region.
(2) Energy transmission and distribution: energy transmission and distribution refers to the capacity of roads and railways to distribute coal, and pipelines and networks to distribute oil, gas and electricity. The changes in the total consumption and consumption structure of various energy varieties will have an impact on the infrastructure of energy transmission and distribution.
(3) Energy consumption: In the end-use sub-system, energy is consumed to provide energy services, such as passenger transport, cooling comfort, and illumination. The energy demand is mostly determined by the industry, building and transportation. In this study, we referred to the indicator selection in World Energy Outlook 2020 released by International Energy Agency. The impact factors of energy consumption are mainly divided into three categories: (a) energy consumption of the production department, which mainly depends on GDP, economic structure, energy intensity, and energy mix; (b) building energy consumption, which mainly depends on population, urbanisation rate, per capita household energy consumption, public per capita residential area, energy consumption per unit area, and energy mix; (c) energy consumption of the commercial transportation, which mainly depends on traffic turnover and energy mix; and energy consumption of the non-commercial transportation, which mainly depends on vehicle population, average annual mileage, the number of private vehicles per thousand, population, and energy mix.

(4) Energy conversion: Advanced energy conversion technologies effect energy conversion efficiency, and the efficiency further effects the accounting of total primary energy supply.
(5) The economic development plans and carbon constraints for the energy system transition: the target of economic and human livings development and carbon peak and carbon neutrality will impact energy transition including energy intensity, energy mix, energy efficiency, non-fossil electrification level and energy technologies in various sectors. Other impact factors are indirectly effected by GDP, economic structure, population, and urbanisation rate.

2.1.2. Energy consumption transition analysis

In this manuscript, the energy system transition analysis starts with the transition of energy consumption and is followed by the analysis of its influence on energy conversion and energy supply. For energy end-use consumption, three energy consumption sectors are distinguished in this model: production sector, building sector and transportation sector. Several types of energy could be used to fulfil the energy consumption. Coal to gas or electricity, and oil to electricity, in different sectors are mainly adopted to realise energy consumption transition with the purpose of reducing CO_2 emission, decreasing energy intensity, improving technologies, and finally changing the amount and structure of energy end-use consumption.

2.2. Mathematical formulation

The energy transition analysis model is solved using the 'LINPROG' equation solver in Matlab. On the basis of the framework in Fig. 1, we propose a quantitative analysis model to discuss the energy system transition including energy consumption, energy conversion and energy supply model. In the terms of energy types, coal, oil, natural gas, electricity, and heat are considered according to the items in the energy balance table. Coal consumption comprises total coal (e.g. raw coal, washed coal, cleaned coal) and coking products (e.g. coke, coke oven gas). Oil products are, for example, crude oil, gasoline, and kerosene. Natural gas consumption comprises natural gas and liquefied natural gas (LNG). Electricity consumption is calculated based on physical quantities. The power generation coal consumption method is used for standardisation. The time period of the study is 2015–2050.

We trace energy flows from consumption to supply to build a model of the entire energy system. First, the amount of end-use energy (standard quantity) is calculated by sector and energy type; second, the end-use data is converted into the amount of primary energy with the energy conversion efficiencies; finally, primary energy supply is determined by local production quantity, imports, exports, and forecasted end-use consumption.

2.2.1. Energy consumption module

Considering the disparity of the driving mechanism and impact factor, we build an energy consumption model of the production sector, building sector and transportation sector separately.

(1) Energy consumption module of the production sector

The production sector in this study includes sub-sectors: agriculture, industry and construction industry. Energy consumption in the industry sector is calculated with Eq. (1).

$$\begin{aligned} EC^{PS}_{i,j,t} &= EM_{i,j,t} \times EEU_{i,t} + \Delta EC_{i,j,t} \\ &= EM_{i,j,t} \times GDP_{t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{GDP}_{t}\right) \times IS_{i,t} \times EI_{i,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{EI}_{i,t}\right) + \Delta EC_{i,j,t} \end{aligned} \tag{1}$$

where i, j, t, t_0 are sub-sector, energy type, time, base year, respectively; $EC^{PS}_{i,j,t}$ is amount of energy j consumed by sub-sector i of the production sector in year t, in Mtce; $EM_{i,j,t}$ is proportion of energy j in the end-use energy of sub-sector i in year t, reflecting the mix of energy consumption in sub-sector i; $EEU_{i,t}$ is sum consumption of the energy end-use of sub-sector i in year t, in Mtce; $\Delta EC_{i,j,t}$ is consumption change (increase or decrease) for energy j through the substitution of other types of energy for sub-sector i in year t, in Mtce; GDP_{t_0} is GDP of the base year, in CNY; $IS_{i,t}$ is proportion of the added value of sub-sector i in the GDP of the whole society in year t, reflecting the industrial structure; EI_{i,t_0} is energy intensity of sub-sector i in the base year, in Mtce·CNY^{-1}; R^{GDP}_{t} is GDP change rate in year t; $R^{EI}_{i,t}$ is energy intensity change rate of sub-sector i in year t.

Next, we calculate the total end-use energy of the sub-sector of the production sector by using Eq. (2).

$$EC^{PS}_{i,t} = \sum_{j} EC^{PS}_{i,j,t} \tag{2}$$

(2) Energy consumption module of the building sector

The building sector in this study includes sub-sectors: urban building, rural building and public building. Energy consumption in the building is calculated with Eq. (3).

$$\begin{aligned} EC^{BS}_{i,j,t} &= EM_{i,j,t} \times EEU_{i,t} + \Delta EC_{i,j,t} \\ &= EM_{i,j,t} \times FS_{i,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{FS}_{i,t}\right) \times EI_{i,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{EI}_{i,t}\right) + \Delta EC_{i,j,t} \end{aligned} \tag{3}$$

where $EC^{BS}_{i,j,t}$ is amount of energy j consumed by sub-sector i of the building sector in year t, in Mtce; FS_{i,t_0} is floor space for sub-sector i in the base year, in m^2; $R^{FS}_{i,t}$ is floor space change rate of sub-sector i in year t.

The floor space ($FS_{i,t}$)of each type of building in year t is calculated by Eqs. (4) and (5):

$$FS_{u,t} = P \times R^{U}_{t} \times RA_{u,t} \tag{4}$$

$$FS_{r,t} = P \times \left(1 - R^{U}_{t}\right) \times RA_{r,t} \tag{5}$$

where $FS_{u,t}$ and $FS_{r,t}$ are the floor space of urban and rural residential building in the year t, respectively; P is the population in the year t; R^{U}_{t} is the urbanisation rate in the year t; $RA_{u,t}$ and $RA_{r,t}$ are residential area per capita in urban and rural areas in the year t, respectively.

Next, we calculate the total end-use energy of the building sector by using Eq. (6).

$$EC^{BS}_{i,t} = \sum_{j} EC^{BS}_{i,j,t} \tag{6}$$

(3) Energy consumption module of the transportation sector

The transportation sector is composed of commercial transportation (e.g. passenger transport and freight transport) and non-commercial transportation (e.g. private vehicle).

Energy consumption in the commercial transportation is calculated with Eq. (7).

$$\begin{aligned} EC^{CT}_{i,j,t} &= EM_{i,j,t} \times EEU_{i,t} + \Delta EC_{i,j,t} \\ &= EM_{i,j,t} \times TT_{i,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{TT}_{i,t}\right) \times EI_{i,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R^{EI}_{i,t}\right) + \Delta EC_{i,j,t} \end{aligned} \tag{7}$$

where $EC_{i,j,t}^{CT}$ is amount of energy j consumed by sub-sector i of the commercial transportation sector in year t, in Mtce; TT_{i,t_0} is traffic turnover for sub-sector i in the base year, in number of people·km; $R_{i,t}^{TT}$ is traffic turnover change rate of sub-sector i in year t.

Similarly, the energy consumption in the non-commercial transportation (i.e. private vehicle) sector can be calculated with Eq. (8)

$$
\begin{aligned}
EC_{j,t}^{PV} &= EM_{j,t} \times EEU_t + \Delta EC_{j,t} \\
&= EM_{j,t} \times VP_{t_0} \times \prod_{k=t_0+1}^{t} \left(1+R_t^{VP}\right) \times AAM_{t_0} \times \prod_{k=t_0+1}^{t} \left(1+R_t^{AAM}\right) \times EI_{t_0} \times \prod_{k=t_0+1}^{t} \left(1+R_t^{EI}\right) + \Delta EC_{j,t}
\end{aligned} \tag{8}
$$

where $EC_{j,t}^{PV}$ is amount of energy j consumed by non-commercial transportation sector in year t, in Mtce; VP_{t_0} and AAM_{t_0} are vehicle population and average annual mileage for non-commercial transportation sector in the base year; R_t^{VP} and R_t^{AAM} are vehicle population change rate and average annual mileage change rate for non-commercial transportation sector in year t, respectively.

The vehicle population for private vehicles VP_{t_0} is calculated by Eq. (9):

$$VP_t = P_t \times N_t \tag{9}$$

where P_t is the population in the year t; N_t is the number of private vehicles per thousand in the year t.

On the basis of Eqs. (7) and (8), we can calculate the total end-use energy of the transportation sector by using Eq. (10).

$$EC_{i,t}^{TS} = \sum_j EC_{i,j,t}^{CT} + \sum_j EC_{j,t}^{PV} \tag{10}$$

On the basis of Eqs. ((1), (3), (7) and (8), we can calculate the total energy consumption according to the energy type, presented in Eq. (11).

$$EC_{j,t} = \sum_i EC_{i,j,t}^{PS} + \sum_i EC_{i,j,t}^{BS} + \sum_i EC_{i,j,t}^{CT} + EC_{j,t}^{PV} \tag{11}$$

2.2.2. Energy conversion and supply module

In this section, the balance of energy consumption, conversion, supply, import, and export of fossil energy and renewable energy is modelled separately because of differences in their conversion process and calculating method.

1. Fossil energy conversion and balance

Primary fossil energy consists of coal, oil and natural gas. Supply of primary fossil energy is calculated with Eq. (12).

$$FES_{m,t} = LP_{m,t} + Im_{m,t} + OI_{m,t} \tag{12}$$

where $FES_{m,t}$ $LP_{m,t}$, $Im_{m,t}$ and $OI_{m,t}$ are total supply, local production, import and opening inventory of primary fossil energy m in year t, respectively, in Mtce.

Consumption for primary fossil energy m is calculated with Eq. (13).

$$FEC_{m,t} = EEU_{m,t} + \frac{PEU_t \times PGM_{m,t}}{PGE_{m,t}} + \frac{HEU_t \times HGM_{m,t}}{HGE_{m,t}} + Ex_{m,t} \tag{13}$$

where $FEC_{m,t}$, $EEU_{m,t}$ and $Ex_{m,t}$ are total fossil energy consumption, quantity of end-use energy and export of fossil energy m in year t, respectively, in Mtce; PEU_t and HEU_t are total end-use power and total end-use heat, respectively, in Mtce; $PGM_{m,t}$ and $HGM_{m,t}$ are proportion of power generated by fossil energy m in total end-use power and heat generated by fossil energy m in total end-use heat, reflecting the power generation mix and heat generation mix, respectively; $PGE_{m,t}$ and $HGE_{m,t}$ are power generation efficiency and heat generation efficiency of fossil energy m, respectively.

2. Renewable energy conversion and balance

The renewable energy in this study includes solar, wind, hydropower and other. Supply of renewable energy is calculated with Eq. (14).

$$RES_t = \sum_n \left(REP_{n,t_0} \times \prod_{k=t_0+1}^{t} \left(1+R_t^{REP}\right) \right) \tag{14}$$

where RES_t is total supply of renewable energy; REP_{n,t_0} is production of renewable energy n in the base year, in Mtce; R_t^{REP} is change rate of production of renewable energy n in year t.

Consumption for renewable energy is calculated with Eq. (15).

$$REC_t = PEU_t + Ex_{\text{electricity},t} - \sum_m PEU_t \times PGP_{m,t} \tag{15}$$

where REC_t and $Ex_{\text{electricity},t}$ are total consumption of primary renewable energy and net electricity exports in year t, respectively.

Next, we obtain the total supply and consumption Eq. (16).

$$\sum_m FES_{m,t} + RES_t = \sum_m FEC_{m,t} + REC_t \tag{16}$$

2.2.3. Carbon emission module

As mentioned above, carbon emissions in the region include direct carbon emissions and indirect carbon emissions, which can be calculated according to Eqs. (17) and (18) respectively.

$$DCE_{j,t} = EC_{j,t} \cdot EF_j \cdot O_j \tag{17}$$

$$ICE_t = \Delta Q_t \cdot EF_{\text{electricity},t} \tag{18}$$

where $DCE_{j,t}$ is the direct carbon emissions from energy j consumed in year t, in Mt; EF_j is the carbon emission factor of the energy type j; O_j is the oxidation ratio of the energy type j; ICE_t is the indirect carbon dioxide emissions generated by purchased electricity in year t, in Mt; ΔQ_t is the amount of electricity traded in year t, in MW; $EF_{\text{electricity},t}$ is the carbon emission factor of the electricity mix.

Carbon emission factors of different types of fossil fuels are referred to Ref. [46], under which the carbon emission factors of coal, oil, gas are 2.66 tCO_2/tce, 1.73 tCO_2/tce, and 1.56 tCO_2/tce respectively.

On the basis of Eqs. (17) and (18), we can calculate the total carbon emissions in the region, presented in Eq. (19).

$$CE_t = \sum_j DCE_{j,t} + ICE_t \tag{19}$$

The energy.

2.3. Scenario setting for the case study of Sichuan province

On the basis of the built ETAM, a case study of energy transition in Sichuan Province is developed. In this study, ETs of 2030 and 2050 are planned while considering the historical development trend and future development assumptions. Next, we introduce the current energy status, trends, and problems of Sichuan and then the model parameters and scenario setting. We take the economic development target (GDP), population, urbanisation rate, industrial structure, housing area per capita, car ownership per thousand people, and passenger and freight turnover as common parameters. The energy intensity of agriculture, industry and construction, the energy consumption per building area of various types of buildings, the fuel consumption rate per vehicle turnover or mileage, and the energy mix of each energy end-use sector were considered to be set in different scenarios.

2.3.1. Current energy status and trends

Sichuan Province is a distinct region in China from the energy and economic perspectives. The annual GDP growth rate of Sichuan Province was 7.2% in 2015–2020, higher than that of China (5.8%; China-National-Bureau-of-Statistics, 2021). Sichuan is also authorised by the National Energy Administration as a national clean energy demonstration province. Sichuan has the advantage of its abundant resources of hydropower and natural gas. In 2020, with 5.9% of the population and 5.1% of the land in China (China-National-Bureau-of-Statistics, 2021), Sichuan Province occupied both 24% of the recoverable natural gas reserve (17.8 trillion m^3) and technical recoverable hydropower capacity (145 GW) in China (Sichuan-Government, 2017). In 2019, total energy consumption was 207.9 Mtce, calculated by using the methods of equal electricity value (Sichuan-Provincial-Bureau-of-Statistics, 2020).

The province provides local energy consumption mainly supported by hydropower and plays an important role in the national energy security strategy. Hydropower accounted for 81.3% of the total power generation capacity of Sichuan Province, and its natural gas production reached 35.6 billion cubic metres, accounting for 24% of Chinese total production in 2017. Approximately 57% of the generated electricity and 56% of the produced natural gas in Sichuan Province were exported to China's eastern regions (China-National-Bureau-of-Statistics, 2018). However, Sichuan is still facing several energy-related problems. The energy intensity was 0.49 tce/10^4 yuan higher than the national average (0.41 tce/10^4 yuan) in 2018, indicating low energy utilisation efficiency in the current period. A large share of the high-carbon energy supply, including coal and oil, is imported from other regions, and over 50% of the provincial low-carbon energy, including natural gas and hydropower, is exported to other regions. Fig. 2 illustrates the energy supply–demand gap of Sichuan Province in 2015. The bars in Fig. 2 represent the ratio of energy supply–demand gap.

As stated, the distinguishing feature of energy supply–demand system of Sichuan Province is that a large part of fossil energy with high carbon emission factor is imported while 57% of electricity mainly zero-carbon hydropower and 56% of natural gas is exported. To achieve the target of carbon peak before 2030 and carbon neutrality before 2060, it is urgent to take the energy system transition in terms of technological

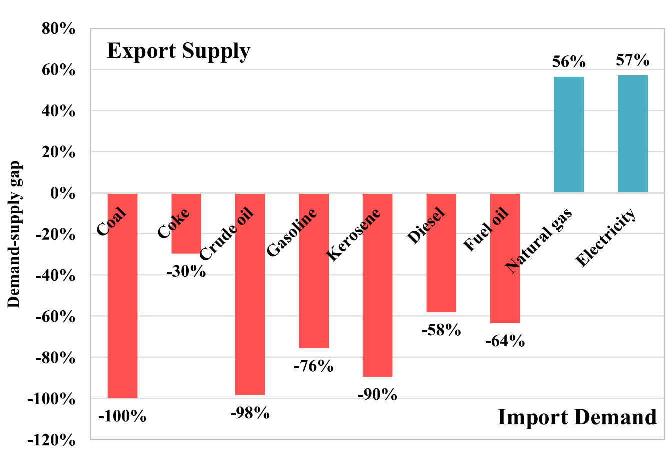

Fig. 2. Energy supply–demand gap of Sichuan Province, 2015.

progress, energy substitution and electrification in end use. Most of the literature has focused on the development of a specific energy type in Sichuan Province, for example, as renewable energy, rural energy, and natural gas [47–52]. Therefore, to present the energy pathway under the target of carbon peak and carbon neutrality, this manuscript analyses the entire energy system in Sichuan Province use the energy transition analysis model including energy supply, energy conversion and energy consumption in terms of production sector building sector and transportation sector by employing the scenario analysis.

2.3.2. Model parameters

Five types of data are introduced according to the ETAM: population, urbanisation, economic development and economic structure, and energy resource.

(1) Population

Population is an important factor that effects energy consumption growth. From 2010 to 2020, the permanent resident population of Sichuan Province increased from 80.42 million to 83.71 million. Thus, the average population growth rate of Sichuan Province was lower (0.3%) than that of China from 2010 to 2020 (0.5%). The main reason for this difference is that Sichuan Province is a typical labour export province of China. Most commonly, these migrants prefer to move to developed regions such as Beijing, Shanghai, and Guangdong because of their well-built infrastructure (public transportation, education, and medical services) and high-income job opportunities. Notably, the population growth rate of China increased to 0.79% in 2015 because the central government implemented its nationwide Two-Child Policy. The average annual growth rate of the population in Sichuan Province increased to 0.6% from 2015 to 2020 along with economic development (China-National-Bureau-of-Statistics, 2021). Therefore, the expected average annual growth rate of the population is 0.7% from 2020 to 2025. Thus, the average annual population growth rate has decreased by 0.1% every five years. The permanent resident population in Sichuan Province is expected to be 90.19 million and 94.10 million in 2030 and 2050, respectively.

(2) Urbanisation

From 2011 to 2019, the share of urban population of Sichuan Province increased from 41.8% to 53.8% (Sichuan-Provincial-Bureau-of-Statistics, 2020). Compared with urban areas, the residential energy consumption per capita of rural areas increased significantly and transcended the former (Table 1). By 2020, the urbanisation rates of developed regions in China reached 70% in, for example, Guangdong, Zhejiang, and Jiangsu, and 80% in Beijing, Shanghai, and Tianjin (China-National-Bureau-of-Statistics, 2021). Considering the rapid progress of urbanisation, in 2030 and 2050, we project that the urbanisation rate of Sichuan will be 68% (e.g. Guangdong, Zhejiang, and Jiangsu in 2017) and 80% (e.g. Beijing in 2017), respectively, reaching the current level of developed regions in China.

(3)Economic development

The increase of GDP is the main influencing factor of energy consumption growth in Sichuan Province. From 2011 to 2020, Sichuan

Table 1
Residential energy consumption per capita (toe/person) of Sichuan Province [53,54].

Area	2010	2015
Urban area	0.1837	0.1931
Rural area	0.0942	0.3852

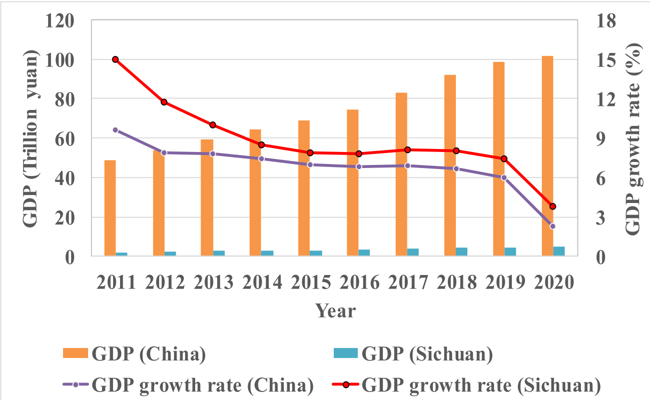

Fig. 3. GDP and GDP growth rate of Sichuan Province and China's average (2011–2020).

Province's GDP increased from 1805.2 billion yuan to 4859.9 billion yuan (Fig. 3). With an average annual growth rate of 8.8%, Sichuan Province has simultaneously undergone rapid industrialization, urbanisation, and motorization. Fixed-asset investment, which consumes a tremendous amount of high-energy-intensity building materials such as steels and cement, is the main driver of the rapid growth in GDP in the province. Because China is entering the 'New Normal' period and the impact of COVID-19, the high-speed development of the economy of Sichuan Province will not be maintained.

In 2020, per capita GDP of Sichuan Province was 58,126 yuan, which was much lower than the national average level (72,000 yuan). We expect Sichuan Province to accelerate its economic development to catch up with the national level; thus, in the future, its GDP growth rate should be much higher than the national average. Based on the consultation of the Sichuan Provincial Government, the per capita GDP of Sichuan Province in 2030 is expected to reach the level of Chongqing in 2019 (76,000 yuan), and this target requires a GDP growth rate of 6.5% from 2015 to 2030. Additionally, the per capita GDP of Sichuan Province in 2050 is expected to reach the level of Jiangsu in 2019 (120,000 yuan), and this target requires a GDP growth rate of 4.9% from 2030 to 2050.

(4) Economic structure

During the 13th Five-Year Plan (2016–2020), the government of Sichuan Province optimized the economic structure by enhancing the proportion of tertiary industry, particularly the financial services and real estate industries [55]. The energy intensity of tertiary industry is lower than that of industry and construction industry. Hence, the increasing proportion of tertiary industry decreased the energy consumption. From 2011 to 2019, the shares of the primary and industry and construction industry of Sichuan Province decreased from 14% to 50%–10.3% and 37.3%, respectively, and the share of tertiary industry increased from 35% to 52.4%. Therefore, according to the current change rates and long-term development plan of Sichuan Province (Sichuan-Provincial-Bureau-of-Statistics; The 14th Five-Year Plan of Sichuan Province and the outline of the Long-range Goals for 2035), the shares of the secondary and tertiary industry of Sichuan will be 32% and 61% in 2030 and 28% and 69% in 2050, respectively.

(5) Energy resources

According to the present plans of exploitation and the resource reserves [55–58], the energy resource availability of fossil energy and renewable power is presented in Table 2. Average annual running hours of Hydropower , Coal-fired power, Natural gas-fired power, Photovoltaic power and Wind power is 4500, 4500, 4500, 1300, and 2000 h.

The maximum production capacity of coal was 47.6 Mtce from 2015 to 2050 in this study [55,57], which means that if the coal demand is greater than the maximum mining amount, we can only rely on imports to meet the demand; if the demand is insufficient to the maximum mining amount, mining can be carried out according to the demand. Crude oil production declined from 0.20 Mtoe in 2010 to 0.1 Mtoe in 2018 in Sichuan Province (Sichuan statistical yearbook, 2019). Crude oil imports were maintained at 3 Mtoe before 2014; the petroleum product demand was approximately 15 Mtoe. To satisfy local demands, the government of Sichuan Province approved the construction of a refinery with a capacity of 10 Mt/year (Sichuan-Government, 2011). The refinery began operating in 2014, significantly increasing the crude oil imports of Sichuan Province.

The total recoverable natural gas in Sichuan Province is 17.8 trillion cubic metres [58], accounting for 24% of the reserve of China and ranking first in China (Ministry of Land and Resource of PRC, 2017). These recoverable natural gas resources include 8.8 trillion cubic metres of conventional natural gas, 2.4 trillion cubic metres of tight gas, and 10.0 trillion cubic metres of shale gas. However, the proven shale gas resource contributes less than 1% to the total recoverable shale gas resource [58]. With technology development, the proven rate of natural gas resources is expected to increase to 34% in 2020. The natural gas production is expected to increase from 24.9 Mtoe in 2015 to 41.0 Mtoe in 2020, including 9.1 Mtoe of shale gas.

According to the 14th Five-Year Energy development plan of Sichuan, the comprehensive energy production capacity will be about 257 million tons of standard coal in 2025. The total installed power capacity of the province is about 150 million kW, of which the installed hydropower capacity is about 105 million kW, the installed thermal power capacity is about 23 million kW (including coal power, gas power, biomass power, etc.), the installed wind power capacity is 10 million kW, and the installed photovoltaic power capacity is 12 million kW. Natural gas production capacity increased steadily. Clean energy installations accounted for about 88%. The proportion of non-fossil energy consumption is around 42%, and that of natural gas is around 19%.

2.3.3. Scenarios setting

Scenario analysis of energy transition is conducted to analyse the uncertainty of influencing factors' contributions, such as technological progress, energy substitution policy and renewable power penetration, because over decades, these factors will substantially change. Two scenarios of energy system development, including business as usual (BAU) and ET, are designed. The economic and social development parameters of the BAU scenario and ET scenario are consistent. The relevant data from 2015 to 2020 in the BAU scenario mainly refer to the statistical yearbook of China or provinces and cities. The data after 2020, such as the energy mix of subsectors' end use, thermal power efficiency, heating proportion, and efficiency, will remain unchanged based on the 2015 data. Compared with the BAU scenario, the ET scenario first considers the technological progress more progressively to decrease energy intensity in production sector and energy efficiency in building sector and

Table 2
Energy resource availability of Sichuan Province in 2050.

Energy	Coal (million ton of standard coal equivalent)	Oil (million ton of standard oil equivalent)	Natural gas (billion cubic metres)	Hydropower (billion kW)	Wind (million kW)	Photovoltaic (million kW)
Energy resource	47.6	0.2	100	140	50	150

transportation sector. Next, energy mix transition in production sector, building sector and transportation sector is conducted through energy substitution. Lastly, since the renewable power penetration rate will significantly impact CO_2 mitigation, we further considered different renewable power penetration rate. The scenario setting is as follows.

(1) Energy intensity

There are two ways to reduce the end-use energy intensity while maintaining high-speed economic development. One way is to shut down the low-efficient factories and implement stricter standards of energy consumption for a unit facility, to reduce the actual energy consumption. The other way is to replace the traditional manufacturing industry with high-value-added industries, to accelerate economic development. In the BAU scenario, according to the current situation, we set a more conservative rate of decline in energy intensity. According to the recently released targets of China's carbon peak in 2030, the energy intensity should be decreased with an annual decreasing rate of 3% at least. In this paper, agriculture is referred to as primary industry; Industry and construction are referred to as secondary industry; Building and transportation are referred to as tertiary industry. Based on the consultation of the Sichuan Provincial Government, we assume that the decreasing rates of energy intensity of primary, secondary, and tertiary industry are 3%, 4%, and 3% from 2015 to 2030 and 2%, 2%, and 2% from 2030 to 2050, respectively. Thus, the end-use intensity of the primary, secondary, and tertiary industry of Sichuan Province will be 0.06 tce/10^4 yuan, 0.53 tce/10^4 yuan, and 0.15 tce/10^4 yuan in 2030 and 0.04 tce/10^4 yuan, 0.39 tce/10^4 yuan, and 0.10 tce/10^4 yuan in 2050, respectively. In the ET scenario, with the advancement of technology and development of emerging industries, we set a more aggressive rate of decline in energy intensity so that the end-use intensity of the primary, secondary, and tertiary industry of Sichuan Province will be 0.05 tce/10^4 yuan, 0.45 tce/10^4 yuan, and 0.13 tce/10^4 yuan in 2030 and 0.03 tce/10^4 yuan, 0.28 tce/10^4 yuan, and 0.08 tce/10^4 yuan in 2050, respectively.

The relevant data results of the energy intensity of production sector, building sector and transportation sector in Sichuan Province are shown in Table A1, Table A2 and Table A3, respectively (see Appendix A).

(2) The transformation of energy consumption structure

The energy consumption structure of each sector in 2015 comes from the Sichuan Statistical Yearbook (Sichuan-Provincial-Bureau-of-Statistics, 2016). Based on the data from the Sichuan Statistical Yearbook and development projections, we calculated the energy consumption structure of each sector in 2030 and 2050 under each scenario. We considered coal to gas, coal to electricity, oil to gas, and oil to electricity in two aspects: end use of production sector, building sector, transportation sector and that of the power sector. In the end use of production, coal-fired industrial boilers, coal-fired self-generation power plants, coal-fired flue-cured tobacco plants, and coal-fired building material kilns will change to use electrical boilers. The relevant data results of the energy consumption structure transformation of production sector, building sector and transportation sector in Sichuan Province are shown in Table A4, Table A5 and Table A6, respectively (see Appendix A).

Table 3
Scenario setting of thermal power.

	Proportion in thermal power	
	Coal power	Gas power
BAU(2030)	85%	15%
BAU(2050)	65%	35%
ET (2030)	74%	26%
ET (2050)	20%	80%

(3) Energy efficiency

The relevant data results of the energy efficiency of building sector and transportation sector in Sichuan Province are shown in Table A7 and Table A8, respectively (see Appendix A).

(4) Renewable penetration rate

In the power sector, coal power generation will gradually decrease while renewable power and gas power will increase. In the BAU scenario, we set a conservative rate of decline of coal power proportion in thermal power generation; in the ET scenario, we set a more aggressive rate of decline (Table 3). Based on the resource volume data of Sichuan Province, we set different renewable energy penetration rates for the two scenarios. In the BAU scenario, the penetration rate of renewable energy in 2050 is 93.2%, and in the ET scenario is 95.8%.

3. Results and discussion

3.1. Scenario analysis results comparison

With the data input and scenarios' setting, the planning pathways of the BAU scenario and the ET scenario are obtained by employing the ETAM model. For further discussion, the comparison of energy supply, varietal energy end-use structure, and sectorial energy end use in 2030 and 2050 are illustrated.

The energy supply of the BAU scenario will be higher than that in the ET scenario in 2030, but the energy supply of the ET scenario will exceed that in the BAU scenario in 2050. The power generated by hydro, photovoltaic and wind in Fig. 4 is measured by the primary energy quantity calculation. Additionally, in the ET scenario, the energy system transition drives the energy supply structure to become more low-carbon, because a large amount of coal is replaced by gas and electricity, and coal power is replaced by gas power and renewable power. In the ET scenario, the coal supply will continue decreasing, from 89.6 Mtce in 2015 to 52.5 Mtce in 2030, and 18.5 Mtce in 2050. According to Fig. 4, the oil supply will decrease to 30.3 Mtce in 2050 in the BAU scenario and will peak in approximately 2030 and then decrease to 18.9 Mtce in 2050 in the ET scenario. With the rapid urbanisation progress, there will be a large increase in oil consumption for vehicles, leading to an oil consumption increase from 18.5 Mtce in 2015 to 30.3 Mtce in 2030. Subsequently, with the increasing use of electric, hybrid electric, and natural gas-derived vehicles, oil consumption will decrease to 18.9 Mtce in 2050. Additionally, natural gas supply will dramatically increase from 34.7 Mtce in 2015 to 93.6 Mtce in 2030, and 156.0 Mtce in 2050.

Fig. 5 illustrates the energy end-use structure of Sichuan Province in 2030 and 2050. In the BAU scenario, the proportion of coal in energy end use will decrease sharply by 2030, from 32.7% to 16.3%. This decrease is mainly due to the substitution of coal with natural gas and electricity. From 2015 to 2030, the proportion of natural gas increases from 11.3% to 19.3%, and the proportion of electricity increases from 32.5% to 45.2%. By 2050, the energy mix in the BAU scenario will not change much, but the amount will increase from 259.3 Mtce to 306.6 Mtce.

In the ET scenario, the proportion of coal continues to decline, from 32.7% in 2015 to 15.4% in 2030, and to 3.4% in 2050. From 2015 to 2030, natural gas and electricity are the main substitutes for coal, with the proportion of natural gas increasing from 11.3% to 19.8%, and the proportion of electric power increasing from 32.5% to 46.3%; from 2030 to 2050, coal is mainly replaced by electricity, the proportion of natural gas decrease to 17.1%, and the proportion of electricity is further increased to 67.2% in 2050.

Because Chinese government promised that the carbon emission would peak in 2030, coal as a high-carbon energy source will be decreased more substantially in the non-electricity field after 2030.

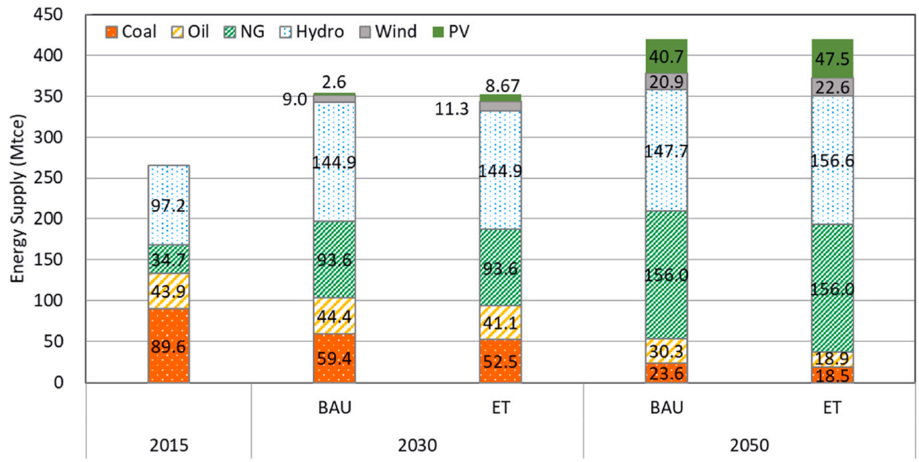

Fig. 4. Energy supply of Sichuan Province (2015, 2030, 2050).

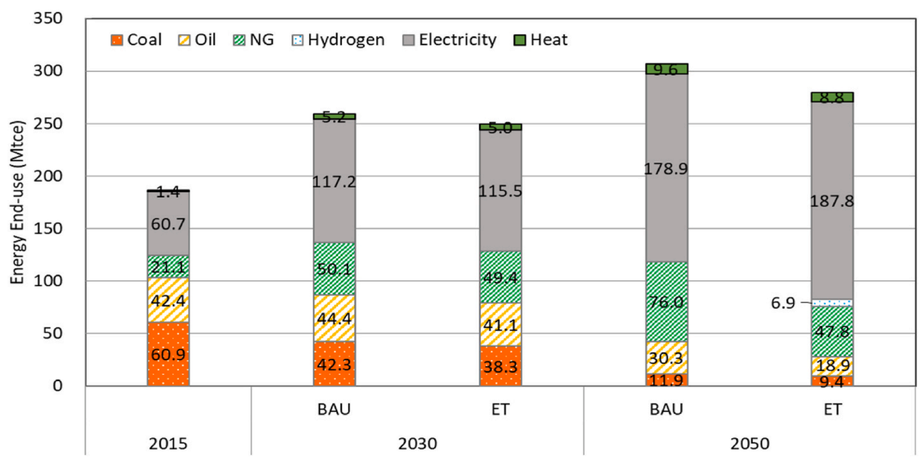

Fig. 5. Energy end-use structure of Sichuan Province (2015, 2030, 2050).

Additionally, the proportion of coal consumption for power generation will increase from 23% in 2015 to 46.7% and 68.2% in 2030 and 2050, respectively. Electricity or gas substitution for coal will effectively reduce coal consumption in the non-electricity field and total coal consumption. By 2030, total coal consumption will be reduced to 46 Mtce, of which energy efficiency improvements, the implementation of coal-to-electricity and coal-to-gas projects will contribute 7.1, 8, and 10.9 Mtce to the reduction, respectively.

Coal should be used in a hierarchical, centralised, clean, and high-efficient manner. Considering that the coal-fired power plants in Sichuan Province mostly operate in the dry season with annual operating hours of 1400 h, substantially challenging to their operation, we suggest implementing a 'Two-Part' tariff for thermal power plants, to maintain the benefits of on-grid sales, and consider guaranteed benefits to ensure the safety of the power supply. In addition, the hydropower and thermal power enterprises are encouraged to actively implement 'hydro-thermal replacement'. To some hydropower stations with regulating capacity, the thermal power generation quotas can be sold at lower prices to achieve a win–win situation for the thermal and hydropower enterprises. In 2015, the hydropower capacity with seasonal regulating capability reached 23.59 GW, accounting for 34% of the total hydropower capacity of Sichuan Province. According to the 13th Five-Year Plan of Sichuan Province, by 2020, the proportion will increase to 38%. Additionally, because the return on investment is low, the enterprises cannot afford the high cost of immigration compensation, land floods, and ecological and environmental problems. Therefore, governmental support from financial and social management aspects is necessary to implement reservoir hydropower projects. Besides, the environmental problems, ecological damage and resettlement problems caused by large-scale hydropower development need to be paid enough attention.

Sichuan Province has introduced policies related to the switch from coal to electricity, including subsidies for the infrastructure of switching from coal-fired boilers to electric boilers and preferential policies for electricity prices. To increase the proportion of clean energy consumption, the government should increase the intensity and scope of subsidies in the short term.

By 2020, the newly added proved reserves of conventional natural gas will be 650 billion cubic metres, and the natural gas production will be 45 billion cubic metres, of which 10 billion cubic metres are shale gas. For the natural gas industry, except for the development of gas-fired power generation, it is also significant to promote gas substitution for coal, especially in large coal-consuming industries (e.g. the iron and steel industry the building material industry). It is practicable to implement LNG vehicles to replace the existing heavy trucks, city buses, and so on. The government should expand the use of natural gas in urban and rural areas and increase the level of gasification. With gradual promotion, every county should be laid with gas pipelines. In key areas, every town should be laid with gas pipelines. In industrial fuel sectors, coal-to-gas projects should be implemented. For industrial parks and industrial concentration areas, measures should be implemented to promote CCHP or centralised heating projects. For energy-intensive sectors, such as steel and building material manufacturing sectors, gas substitution for coal-fired boilers and kilns should be encouraged.

The Third Phase West-to-East Gas Pipeline will be completed to support natural gas transportation. Natural gas production will increase from 26.7 billion cubic metres to 72 billion cubic metres. The development of a gas substitution for coal, distributed gas-fired power generation, and gas-derived vehicles will add 5.5 and 7.5 billion cubic metres of gas demand, respectively. Additionally, the outer-region demand for natural gas will increase from 12.5 to 15.1 billion cubic metres. After 2030, with abundant natural gas resources, to fulfil the increasing electricity demand, Sichuan Province's gas-fired power generation capacity will experience considerable expansion in the foreseeable future. A low-carbon energy, natural gas consumption in non-electricity field will be increased as well.

With an abundant hydro resource, it is promising to form a wind–solar–hydropower system. The system can overcome the discontinuous and unstable disadvantages of wind and solar power with the good, regulated performance of large-scale hydropower stations (i.e., pumped storage power station). More reservoir hydropower stations with seasonal regulating capacity should be built to improve the regulating capability of hydropower during rain and dry seasons. Additionally, small-scale hydropower and coal-fired power stations should be shut down step by step. For electricity end use, it is crucial to promote electricity substitution for the present coal–gas–oil consumption. For residential use, the electrification progress of heating, hot water supply, and cooking should be accelerated. For transportation, electric vehicles and rail traffic should be implemented progressively. For coal-fired and oil-fired boilers, appropriate policies are urgently necessary to guide and impel the implementation of electricity substitution. Notably, transmission to outer regions is not used to control the demand–supply gap but is a means to encourage clean hydropower utilisation in adjacent areas of Sichuan Province. The hydropower transmission channels require large-scale infrastructure that should be constructed and maintained by the grid company and the administrative area where the electricity load is located. Currently, because there are no nationwide mandatory requirements for hydropower consumption, the load areas prefer to build new thermal power plants to boost GDP growth and employment rather than accept clean hydropower. For example, the planned Sichuan-Jiangxi UHVDC (ultra-high voltage direct current) Project would transmit 50 billion kWh of electricity annually but has been suspended for years, and Sichuan Province will abandon over14 billion kWh of hydropower.

Hydropower plants can respond quickly to the load and are recognised as peaking power supplies, but this is not always the case. During the wet season, to make full use of the abundant water resources, hydropower plants need to generate more electricity and most of them operate at a high load rate, making it difficult for them to undertake the task of peaking. At this time, thermal power is necessary to undertake the necessary peaking task to fulfil the peak load demand. During the dry season, the supply of hydropower is insufficient and cannot fulfil the demand alone; thus, thermal power is still necessary as a supplement to the electricity demand. In August 2022, continuous high temperatures and lack of rain led to a sharp increase in electricity demand and a sharp decrease in the supply of hydroelectric power, resulting in a power shortage in Sichuan Province. Under such circumstances, the electricity consumption of industry and commerce is limited to a certain extent. To get rid of similar problems in the short term, we can only increase the coal-fired power generation and coal supply at the national level. The main reasons are as follows: 1) Thermal power accounts for a small proportion in Sichuan, but thermal power accounts for a very large proportion in the whole country. In the past, Sichuan was mainly used as a power supply point. Of course, there was a small amount of electricity is transmitted between provinces, but the amount was very small, and it was difficult to provide enough power to Sichuan in a short time. Power shortages require the grid and the entire coal and thermal power industry to provide support. 2) For energy storage, the amount of energy that can be supplied for a short period of time is too small to be useful. Additionally, most of the hydropower stations in Sichuan Province are in the western areas, away from the load centre, and it is not conducive to the security and stability of the power grid. Thus, some thermal power plants should be built near the load centre. With abundant natural gas resources that are quick to respond and flexible for peaking operation, it is practicable to promote conventional gas-fired power plants and distributed energy systems with gas turbines. In summary, although hydropower is rich in Sichuan Province, a certain size of thermal power installation must be maintained.

Fig. 6 illustrates that the energy end use in the BAU scenario will be much higher than that in the ET scenario in 2030 and 2050, indicating substantial supply–demand gaps if measures are not implemented to promote energy transition. In the ET scenario, the energy consumption of agriculture decreases to 2.5 Mtce in 2050 because of improved energy efficiency and its decreased share in the economic structure. Both the

Fig. 6. Energy consumption by sectors of Sichuan Province (2015, 2030, 2050).

BAU scenario and ET scenario show an increasing trend in total energy consumption, and industry and construction industry has always been the largest energy consumption sector. In the BAU scenario, energy consumption of the industry and construction industry continues to increase, from 128.9 Mtce in 2015 to 151.9 Mtce in 2030, and to 183.9 Mtce in 2050. In the proportion of energy consumption, the proportion of industry and construction industry decreased from 69.1% in 2015 to 58.6% in 2030 and remained basically unchanged in 2050 compared with 2030. In the ET scenario, the energy consumption of industry and construction industry shows a downward trend, from 145.3 Mtce in 2030 to 168.7 Mtce in 2050. In the proportion of energy consumption, the proportion of industry and construction industry decreased to 58.3% in 2030 and to 60.3% in 2050. In the BAU scenario and the ET scenario, the consumption of urban and rural residential building, and commercial traffic showed an increasing trend.

The government should conduct research and discussion with energy enterprises and research institutions, to coordinate and reach consensus from the final demand side for various energies. The mid- and long-term energy development plan of the province should be integrated with all the sectors rather than isolated ones of each sector.

3.2. Overview of energy transition

Based on the methodology and scenario setting described in Section 2, the scenario comparison of energy distribution of Sichuan Province is presented in Table 4.

For coal, in the BAU scenario, with increasing demand and limited resource availability, there will be more coal imports in 2030 than that in the ET scenario. In both scenarios, the coal supply becomes almost self-sufficient in 2050 as coal-fired power generation has been reduced. For natural gas, in the ET scenario, with the massive exploitation of shale gas, the exports will substantially increase. For oil, with industrial transformation and the development of electric vehicles, imports will decrease after 2030 in both scenarios. For power generation, in the BAU scenario, the local power supply will be sufficient in the energy end use, but compared with the ET scenario, it cannot meet all the demand for power transmission to other provinces. In the ET scenario, due to the improvement of energy efficiency (see Table A7and Table A8) and further utilisation of hydropower (see Fig. 4), there is less supplement for coal-fired power and natural gas-fired power compared with BAU scenario.

Fig. 7 illustrates that the energy supply of Sichuan Province in 2030 will be dominated by natural gas and hydropower. For coal consumption, secondary industry use and power generation will each use half. Oil consumption will be mainly used for non-commercial transportation. Hydropower will account for 81.7% of the total power supply, and approximately 34.9% of the electricity will be transmitted to outer regions. The proportions of energy end use in agriculture, industry, construction industry, building and transportation will be 1.2%, 55.4%, 2.8%, 27.1% and 13.5%, respectively.

Fig. 8 illustrates that the amount of natural gas in the energy supply of Sichuan Province in 2050 will further increase and that the amount of oil will decrease. Most of the coal consumption will be centralised and used for power and heat generation, and direct coal consumption for end use will be mostly substituted with gas and electricity; 7.7% of natural gas will be used for power and heat generation, and 30.8% will be directly consumed for end use. Half of the oil consumption will be used for non-commercial transportation. Compared with 2030, in 2050, the proportions of agriculture, industry and construction industry, and rural energy end use will decrease, and the proportion of urban energy end use will substantially increase.

From 2015 to 2030, in the transition scenario, the power demand of Sichuan will increase at an average growth rate of 5.3% annually. The proportion of coal-fired power capacity will decrease from 15.2% to 5.6%; gas-fired power capacity will increase from 1.0% to 1.7%; and non-fossil-fuel-derived power capacity will increase from 83.7% to 92.7%. From 2015 to 2020, the electricity supply is sufficient to fulfil the provincial and outer-region demand. From 2020 to 2030, considering the decommission of existing coal-fired power plants and the reserve limit of developing hydropower plants, the electricity supply will become insufficient to fulfil the increasing demands from outer regions. To manage the possible supply–demand gap, substantial efforts are necessary in promoting wind, solar, and gas-fired power generation. From 2030 to 2050, with the increase in per capita electricity demand, industrial electricity demand for the development of coal-to-electricity and oil-to-electricity projects and big-data centres, if Sichuan still needs to maintain the current amount of hydropower transmitted to the outer regions, the electricity supply in Sichuan will no longer fulfil the increasing demand. Therefore, with full consideration of the electricity demand increase potential of Sichuan Province, the electricity transmission to outer regions should be carefully planned.

Table 4
Energy distribution in the BAU (Business as usual) and ET (Energy transition) Scenarios (Unit: 1 Mtce).

Scenario	Year	Mtce	Coal	Natural Gas	Oil	Power
BAU	2015	Local production	44.0	34.7	0.2	97.2
		Import	45.6	−12.8	43.7	−39.9
	2030	Local production	48.6	93.6	0.2	156.5
		Import	11.8	−37.0	44.2	−54.0
	2050	Local production	22.6	156.0	0.3	209.3
		Import	1.0	−67.4	30.0	−42.2
ET	2030	Local production	43.5	93.6	0.2	164.9
		Import	9.0	−39.1	40.9	−61.9
	2050	Local production	17.7	156.0	0.3	226.7
		Import	0.8	−95.7	18.6	−49.1

3.3. CO_2 mitigation analysis on energy transition pathway

3.3.1. CO_2 emission pathway analysis

According to the results of energy transition in the two scenarios above, we further calculate and demonstrate the carbon emission path in the two scenarios, as shown in Fig. 9. Among them, the dotted line from 2050 to 2060 is obtained by linear extrapolation according to the development trend after 2030. In BAU scenario, Sichuan's carbon emissions peak in 2034 at 279 Mt, an increase of 18% compared with 2015. Carbon emissions in 2060 will be 151 Mt, a 34% reduction from 2015, which cannot meet the national proposed carbon peak target before 2030. Considering the carbon sink of Sichuan province is 47.8 Mt in 2018, the path will not meet the goal of carbon neutrality by 2060. In ET scenario, Sichuan province can achieve a peak of 255 Mt of carbon emissions in 2028, increased by 8% from 2015. Carbon emissions in 2060 will be 13 Mt, a 95% reduction from 2015. With this path, Sichuan province could achieve carbon neutrality by 2058 with 45.1 Mt CO_2 emissions.

3.3.2. CO_2 mitigation effect analysis of energy transition

In order to further demonstrate the carbon reduction effect brought by various measures of energy transition, this section focuses on the detailed analysis of the carbon reduction potential of different end-use sectors by improving energy efficiency, changing energy mix and increasing the proportion of renewable electricity under ET scenario. The results are shown in Fig. 10.

As can be seen from Fig. 10, compared with the carbon emissions in BAU scenario of 151.5 Mt, in 2058, the CO_2 emission in ET scenario decreased by 106.4 Mt to 45.1 Mt. In order to further evaluate the carbon emission mitigation potential of ET scenario with various energy transition schemes of industrial sectors, on the assumption that the parameters in other departments other than industry stay at benchmark level, we first assessed the effect of energy efficiency improvement on the mitigation of carbon emissions in the industrial sector under the energy transition scenario in 2058. The reduction is 6.8 Mt. On this

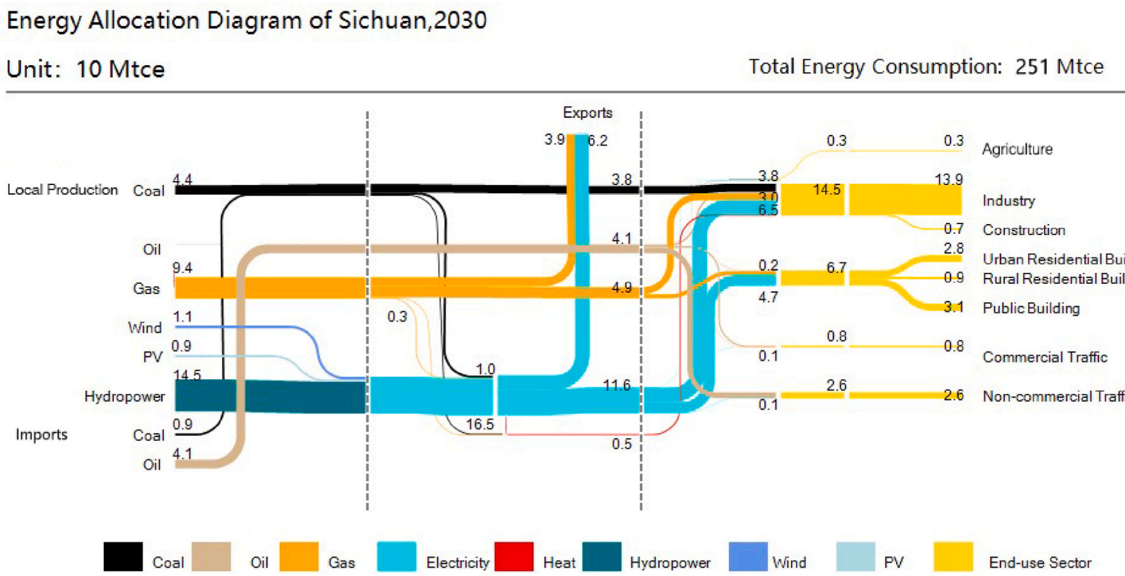

Fig. 7. Energy allocation diagram of Sichuan Province, 2030.

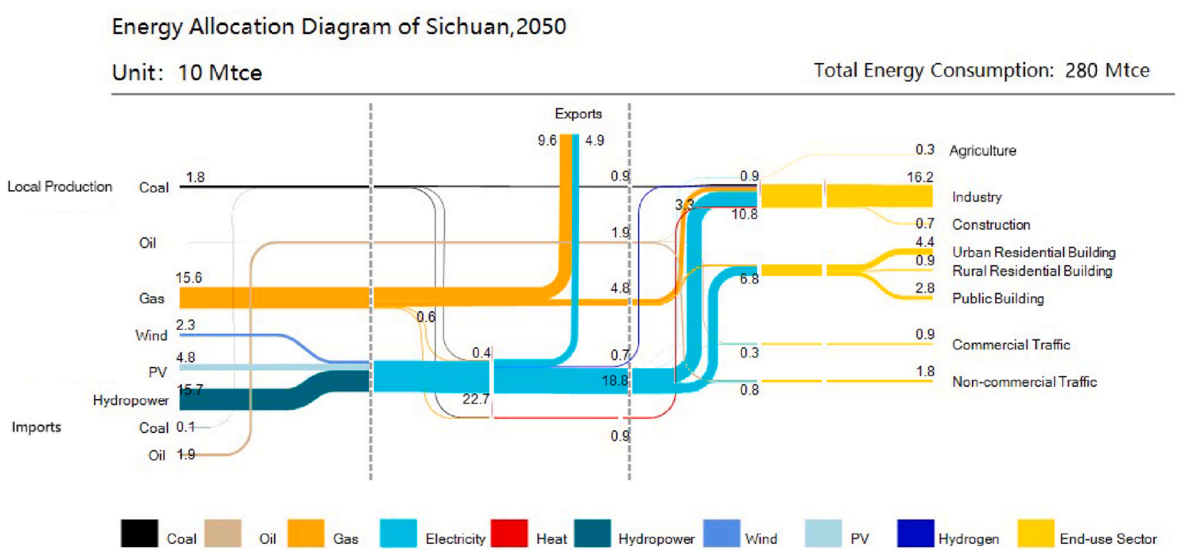

Fig. 8. Energy allocation diagram of Sichuan Province, 2050.

basis, we have analysed the energy mix of the industrial sector (see Table A4) and the carbon reduction capacity of increasing the proportion of renewable electricity (see Fig. 4). And the relative carbon reduction is 42.0 Mt and 3.4 Mt. Then, we use the same methodology to assess the carbon reduction potential of the energy transition in the buildings and transportation sectors. The results show that the energy efficiency improvement, energy mix optimization and the increase in the proportion of renewable electricity in industry, transportation, buildings, and other sectors can reduce CO_2 emission by 13.3 Mt, 87.8 Mt and 5.4 Mt respectively in ET scenario compared to BAU scenario. Though, the linear extrapolation on scenario results of carbon emission from 2050 onwards is a trend estimation rather than an accurate forecast, of which the potential carbon sink is not well considered. If natural carbon sink and industrial CO_2 utilisation technologies are well-developed, the CO_2 emission will be further reduced.

After the carbon-peak and carbon-neutrality targets are raised, power transfers from other regions will be measured through averaged CO_2 emission factor of the power source, so in the future provinces will be willing to bring in renewable power from other regions. We make scenario analysis of energy consumption transition in different sectors, and scenario analysis of the future development time sequence of Sichuan's oversupplied natural gas, hydropower, wind and solar power. According to the difference of supply and demand in different scenarios, we determine the amount of energy sent out for scenario analysis. The results show that, under the requirement of carbon peak in 2028 and carbon neutrality in 2058, the local use of renewable energy should reach 96.0%. According to the contract of electricity transmission from west to east, the local electricity gap in Sichuan can only be met by gas power, which will not achieve the carbon reduction target.

4. Conclusion and policy implications

4.1. Conclusion

This paper provides a comprehensive understanding of Sichuan Province's energy system while considering the economic and social development and the energy-relevant factors, to reveal the energy system transition process from oversupply to overdemand and analyse the

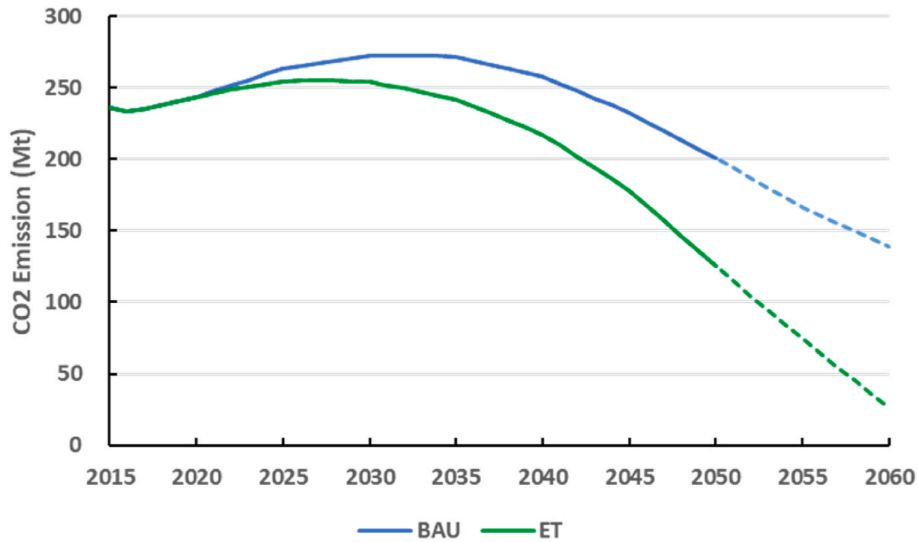

Fig. 9. CO_2 emission mitigation pathway of Sichuan Province in BAU and ET scenario.

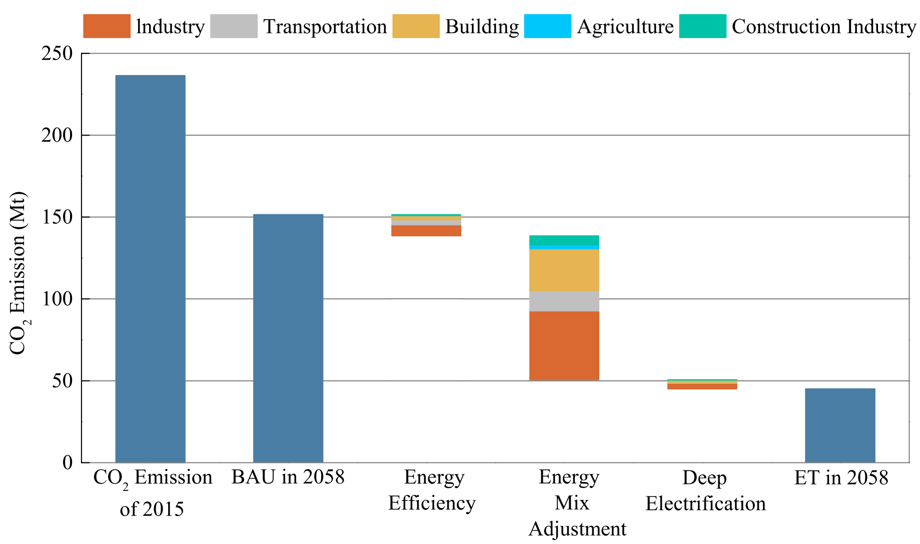

Fig. 10. Quantitative analysis of CO_2 mitigation compared to BAU in 2058.

drivers beyond the trend.

The scenario analysis results indicate the following conclusions.

1) Coal consumption will be further reduced and used in a concentrated way. The supply of renewable power cannot meet the demand of outer-regions, and coal-fired power and natural gas-fired power will be needed to secure exports.
2) In the ET scenario, the increment of renewable energy and gas-fired power generation will further replace coal-fired power generation. The natural gas supply and demand of Sichuan will both increase for coal substitution and clean energy development.
3) Sichuan's carbon emissions peak under BAU scenario and ET scenario occurs in 2034 and 2028 respectively. The BAU scenario cannot achieve carbon neutrality, while carbon neutrality in the ET scenario occurs in 2058.
4) The energy efficiency improvement, energy mix optimization and the increase in the proportion of renewable electricity can reduce CO_2 emission by 13.3 Mt, 87.8 Mt and 5.4 Mt in 2058 respectively in ET scenario compared to BAU scenario.

5. Policy implications

To realise the energy system transition while maintaining high-speed economic development, carbon peak and carbon neutrality, we propose the following policy suggestions for the Sichuan Provincial Government.

1) For the power industry, in the short term, it is practicable to transmit the surplus electricity to outer regions. In the long term, it is more important to improve the power supply structure and plan the operation timing for different power generation facilities, to maintain the electricity demand–supply balance.
2) In consideration of the intermittency and volatility of renewable generation, a certain amount of thermal power must be retained. In addition, pumped storage power station is of great significance to ensure the power supply, ensure the safety of the power grid and promote the absorption of new energy. It is one of the main power sources for the medium- and long-term power development in Sichuan.
3) For the coal industry, to control the total coal consumption and direct combustion of scattered coal, a stricter standard for coal

products is necessary, and more efficient subsidy policies are necessary for the coal-to-electricity transition.

4) In terms of realising the ET goals, although Sichuan Province has reached a consensus on reducing coal consumption and supply, there remains fierce competition between power and natural gas in many industrial sectors. Therefore, the exploration and exploitation of conventional natural gas in the central, west, and northeast of Sichuan Province and shale gas in the south should be accelerated.
5) To achieve carbon neutrality under the ET scenario, the Sichuan's use of renewable energy should reach 96.0%. In the context of electricity transmission from west to east, carbon capture and storage devices should be implemented for gas power generation. In addition, energy mix adjustment, efficiency improvement and electrification level need to be further improved and optimized.

Notably, this paper has a limitation: the effect of financial support and price policy during the energy system transition progress was not mentioned. The energy price and optimization based on marginal abatement costs of different mitigation technologies is not considered. Our team plans to investigate these issues in further research. For futuristic application, the model proposed in this paper can further extended with modules related to energy prices, market supply and demand, and energy security for a more detailed analysis of the energy transition path. At the same time, the model can also be applied to the research of other regional energy transition paths and the construction of cross-regional energy cooperation model.

Credit author statement

Weiqi Li : research design, analysis and discussion, origin manuscript writing, Fan Zhang: modelling and analysis, manuscript writing and editing, Lingying Pan: research design, manuscript editing, Zheng Li: research design and supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2022.101015.

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