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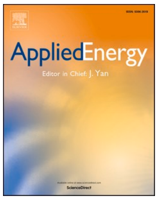

# Transition pathways towards a deep decarbonization energy system—A case study in Sichuan, China

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## HIGHLIGHTS

- It designs a deep decarbonization entire energy system in China firstly.
- It proposes transition pathways sustained by different types of energy.
- The methods and results facilitate decarbonization in any energy system.

## ARTICLE INFO

*Keywords:*
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## ABSTRACT

China has set ambitious carbon emission reduction targets to combat climate change, however, there has been little scientific focus on the achievement of deep decarbonization at the provincial level. The contradiction between rapid economic development and increasing energy utilization exacerbates the difficulty of achieving this goal. Here, we explored the feasibility of fulfilling deep decarbonization in the energy system by 2050 in Sichuan, one of the leading provinces in economic growth in China. Three transition pathways sustained by imported electricity, biomass, and natural gas were developed and simulated using the EnergyPLAN model. All the pathways utilized local hydropower, wind power, and solar photovoltaic resources. These pathways were evaluated using multi-dimensional analysis considering energy self-sufficiency, environmental sustainability, and economic affordability. We found that the energy self-sufficiency rate of the 100% electricity pathway was less than 68%, whereas those of the other pathways were nearly 100%. The $CO_2$ emission reduction differed by pathway, with 100% electricity achieving 91.52%, biomass achieving 90.48%, and natural gas achieving 58.17%. Moreover, all the pathways achieved zero direct $CO_2$ emissions with carbon capture and sequestration (CCS) technology. From an economic perspective, the highest system cost, i.e. 1.3 times that of the reference system, appeared in the 100% electricity pathway after introducing CCS technology, and was comparable to the energy system costs of other provinces in 2050. The methods and results of this study can serve as a basis for facilitating decarbonization in any provincial energy system in the long term.

## 1. Introduction

The continuous accumulation of greenhouse gas (GHG) emissions has led to global environmental deterioration and climate change [1]. While the annual $CO_2$ emissions worldwide increased by 150% from 2000 to 2019 [2,3], the atmospheric $CO_2$ concentration is expected to increase rapidly to double in the 22nd century if the emission level remains the same as that today.

China is one of the largest energy consumers and $CO_2$ contributors worldwide. In 2018, $CO_2$ emissions in China were responsible for approximately 30% of global emissions [4]. The share is expected to increase gradually in the future owing to population growth and industrial expansion. China has been participating in international efforts (such as the Paris Agreement [5]) to mitigate emissions and global temperature rise. Moreover, China has dominated economic development worldwide from 2008 to the present and is deemed vital to global

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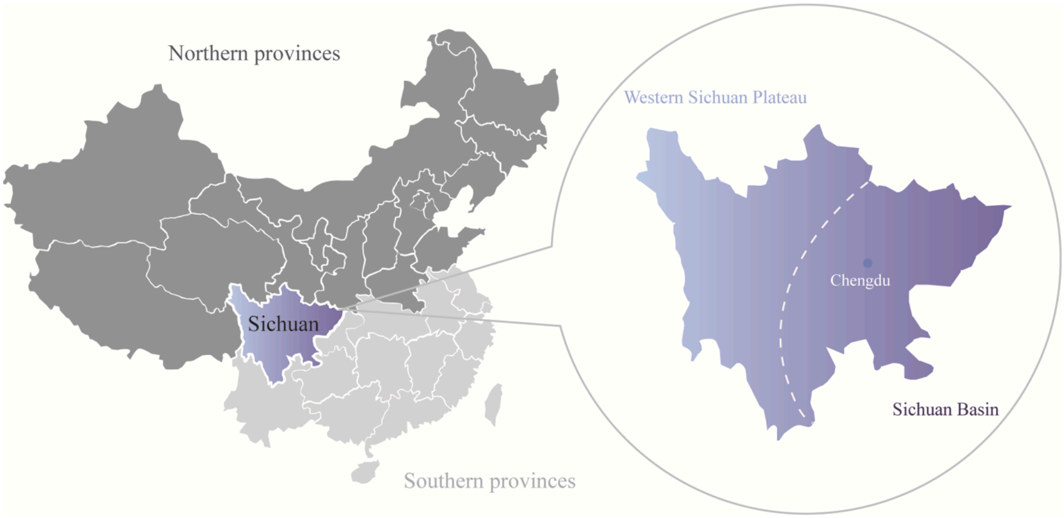

**Fig. 1.** Location of Sichuan Province. The dividing line in the right picture divides Sichuan into two parts, namely that: Sichuan Basin and Western Sichuan Plateau.

economic recovery, especially after the coronavirus disease 2019 pandemic [6,7]. China's important global position from both environmental and economic perspectives, along with the goal of achieving carbon neutrality by 2060 [8], require significant changes in energy use, infrastructure development, and lifestyle.

Future economic growth in China may be concentrated in western provinces owing to the Western Development Strategy proposed in the early 2000s [9] and emphasized again in 2017 [10]. The strategy aimed at narrowing the development gap between the eastern and western regions requires the government to focus on infrastructure construction and formulate preferential policies (such as tax rate reduction) to build economic development centers in the western region. Sichuan, which is in southwest China (Fig. 1), is one of the beneficiaries of this strategy and serves as a leader for future Chinese economic development. Its gross domestic product (GDP) increased from 392 billion CNY in 2000 to 3270 billion CNY in 2016, and the growth rate is expected to remain high in the future [11]. The industrial sector in Sichuan realized an annual added value of 1160 billion CNY in 2016, which was an increase of 7.6% compared with that in the previous year. The added value is expected to continue to grow at a similar rate in the next decade [12]. $CO_2$ emissions from Sichuan and regions with similar positions will undoubtedly influence the total emissions in China and affect global $CO_2$ emissions.

In Sichuan province, the installed capacity of hydropower reached approximately 60 GW in 2015, and is expected to triple by 2030 [13]. Strong incentives have been introduced to mitigate GHG emissions. A yearly fund of up to 100 million CNY has been provided to support key technology projects since 2012 [14], and a subsidy of 130 million CNY has been distributed to govern emissions since 2016 [15]. With its rich renewable resource potential, the challenge is achieving deep decarbonization in Sichuan taking rapid population expansion, energy resource availability, and energy system costs into account.

Many studies concerning $CO_2$ emission reduction and fossil fuel dependence alleviation in China have been conducted. However, most of these studies focused on sustainable energy transition at the national level [16,17] rather than the regional level [18]. Formulating roadmaps of $CO_2$ emission reductions for provinces is essential to achieve the national objective. In addition to the geographical focus, many studies have investigated individual sectors [19,20] or specific renewable technology [21,22] rather than the entire energy system. To the best of our knowledge, there are no studies aimed at deep decarbonization of the entire energy system in provincial regions in China. The Smart Energy System concept, which highlights the importance of cross-sectoral measures in deep decarbonization, was proposed in [23] and elaborated in detail in [24]. It has been applied to many countries [25,26], but has not been investigated in regions with a severe conflict between economic development and carbon emissions. In terms of future energy system design, previous studies have focused more on energy-related $CO_2$ emissions [27,28]; however, other $CO_2$ emissions, such as emissions from industrial processes, are often not included in the emission reduction targets of future deep decarbonization systems.

To fill these scientific knowledge gaps, we proposed a method for future system design and applied it to Sichuan province in China to explore the feasibility of achieving a regional energy system with deep decarbonization by 2050. The proposed system design is universal and can contribute to building a deep decarbonization or even zero $CO_2$ emission system in any region. Three pathways were designed based on imported electricity, biomass, and natural gas (N-gas). They all utilized local hydropower, wind power, and solar photovoltaic (PV) resources. Furthermore, deep decarbonization (-d) and further decarbonization (-z) scenarios were developed in each of these three pathways; their difference lies in whether carbon capture and sequestration (CCS) technology is applied. The effects of implementing these pathways were evaluated from the perspectives of energy self-sufficiency, environmental sustainability, and economic affordability. Hourly simulation of the entire energy system, including all energy sectors (heating and cooling, industrial, transport and power sectors), was conducted in the EnergyPLAN model.

The remainder of this paper is organized as follows: Section 2 introduces the basic information, specifies the natural resource potential, and illustrates the current energy supply mix in Sichuan. Section 3 displays the future Sichuan energy system design from two aspects, namely energy transition pathways and energy sectors. Section 4 presents the modeling tool and methods. Section 5 provides the results from the perspectives of energy self-sufficiency, environmental sustainability, and economic affordability. The discussion and conclusions are presented in Section 6 and Section 7, respectively.

## 2. A case study: Sichuan

### 2.1. Population, geography and GDP

Sichuan, which is located in the inland southwest of China, is the fifth largest province with a total area of 486 000 km$^2$ (Fig. 1). In 2016, the total population of Sichuan was approximately 82.6 million, ranking fourth among the provinces [11]. Geographically, Sichuan can be roughly divided into two regions, namely the Sichuan Basin and the Western Sichuan Plateau (Fig. 1). This specific topography provides rich

**Table 1**
Potential of renewable energy resources in Sichuan.

| Resource | Parameter | This study |
|---|---|---|
| River Hydro Power | Capacity (GW) | 130 |
| | Production (TWh/y) | 541.4 |
| Dam Hydro Power | Capacity (GW) | 15 |
| | Production (TWh/y) | 62.5 |
| Onshore Wind Power | Capacity (GW) | 88 |
| | Production (TWh/y) | 127.4 |
| Solar PV | Capacity (GW) | 105 |
| | Production (TWh/y) | 66.7 |
| Biomass | Potential (TWh/y) | 550 |

hydropower resources and has led to a significant difference in population density of 392 people/km$^2$ in the eastern areas and 32 people/km$^2$ in the western areas.

By the end of 2016, the GDP of Sichuan reached 3270 billion CNY, which was the eighth largest GDP of all the provinces. Meanwhile, the GDP growth rate in Sichuan was 7.7%, which has been more than 1.0% higher than the national average since 2008 [11]. As the bridge of China's eastern and western regions, Sichuan will likely become a priority for policy and investment and become the driver of future GDP growth in China.

### 2.2. Natural resources potential

Sichuan has a wealth of hydropower resources. In 2016, the installed capacity and annual energy generation of hydropower were approximately 72.5 GW and 299 TWh/y, respectively. The share of installed hydraulic capacity in the total power capacity increased from 61% in 2008 to 80% in 2016 [29]. A survey of Sichuan's hydropower resources in 2016 indicated that the technically exploitable installed capacity was nearly 148 GW, whereas the economically exploitable capacity was 145 GW [30]. The technically exploitable installed capacity of dam-type hydropower stations with annual regulation ability was estimated to be a maximum of 15 GW.

Wind power resources, which also have rich potential, are mainly located in the Western Sichuan Plateau. According to meteorological data, the theoretical potential of wind power in the entire province was estimated to be 88 GW [31]. Owing to the spatiotemporal difference, wind power can support the shortage of hydropower when Sichuan undergoes mild droughts because it is mainly concentrated in the winter and spring.

PV technology has been chiefly developed in western rural areas in Sichuan with an installed capacity of 960 MW. The average annual irradiation is expected to be between 4500 MJ/m$^2$ and 6390 MJ/m$^2$. The theoretical installed capacity of solar power in Sichuan is 105 GW [32]. To bridge the gap between power supply and demand, the affluent wind and solar energy resources in Sichuan show a natural complementarity with hydropower; thus, they are expected to be rapidly developed in the following decades.

Due to the lack of actual statistical data on biomass resources, correlation studies and regulatory reports were used to summarize information on available biomass feedstocks in Sichuan. The amounts of individual biomass feedstocks were aggregated to define the collective biomass potential in 2016. The predicted biomass potential in Sichuan in 2050 resembled the potential in 2016 to a large extent, but was updated according to future population projections. The estimation of biomass potential considered food security and the requirement of ensuring local ecological diversity. The total biomass potential was conservatively predicted to be 550 TWh/y by 2050. The detailed estimation method is presented in Section 4.

Considering the diverse topography, geothermal energy in Sichuan can be divided into two categories, namely mountain uplift geothermal resources and sedimentary basin geothermal resources. There are currently 318 ascertained hot spots in Sichuan, including 237 hot spring spots and 81 geothermal wells with a depth of 1800–2500 m and a temperature of 30–90 °C [33]. The total estimated potential of geothermal energy in Sichuan was estimated to be 2619 TWh. The resource potentials in Sichuan are summarized in Table 1.

### 2.3. Current energy system

On the supply side, the electricity mix in Sichuan is hydropower-dominated, but there is a considerable proportion of thermal power generation to provide peak regulation and operation stabilization of the power grid. Hydropower generation accounts for 88.9% of the total electricity generation, whereas wind power currently accounts for 0.5%

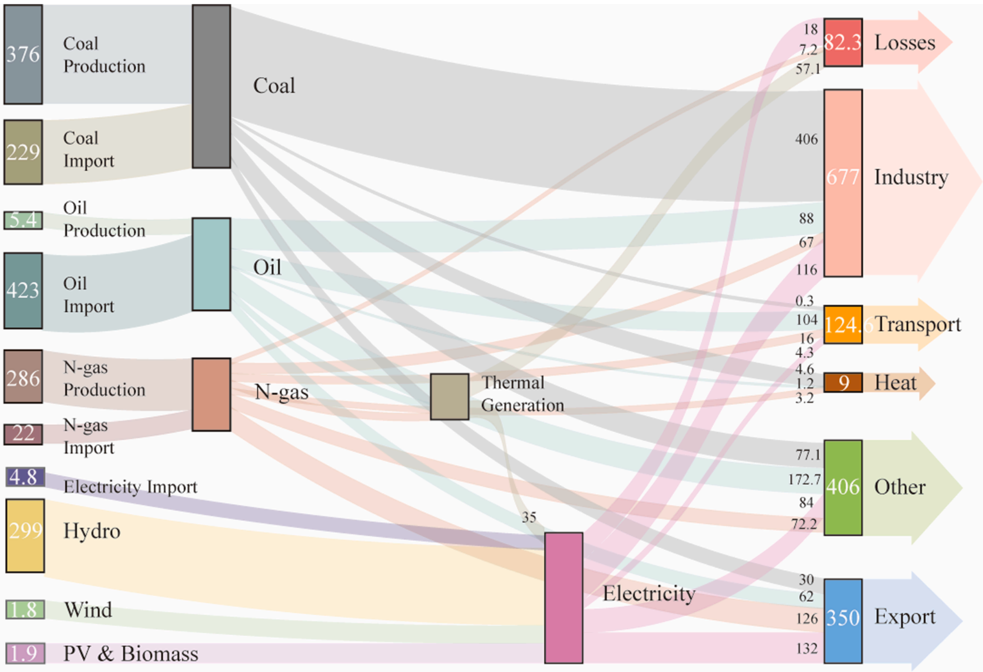

**Fig. 2.** Sichuan energy balance in 2016 (all units in TWh).

**Table 2**
Descriptions of the business-as-usual (bau) scenario and alternative 2050 scenarios.

| Scenario | Scenario abbreviations | Energy type | Do the renewable electricity technologies add to their maximum potential?[a] | Further decarbonization scenario abbreviations | Difference from deep decarbonization scenarios |
|---|---|---|---|---|---|
| BAU 2050 scenario | BAU | Renewable electricity<br>Fossil fuel | No | BAU | – |
| 100% electricity 2050 scenario | ELE-d | Renewable electricity<br>Imported electricity | Yes | ELE-z | Allow CCS technology |
| Biomass 2050 scenario | BIO-d | Renewable electricity<br>Biomass | Yes | BIO-z | Allow CCS technology |
| N-gas 2050 scenario | NCS-d | Renewable electricity<br>N-gas | No | NCS-z | Allow CCS technology |

[a] The detailed installed capacity of the renewable electricity technologies in the above scenarios are presented in Supplementary Table 1.

and solar power only accounts for 0.2% [34] (Fig. 2). Sichuan is short of both coal and oil resources, and its proven reserves account for less than 1% of the total in China [32]. Most coal and oil consumption depends on imports from other regions.

On the demand side, electricity exports and consumption are almost equal. Approximately 53.6% of the generated power was for the demand in Sichuan. The other 46.4% was exported to the eastern provinces of China facing the challenges of unbalanced energy demand and sustainable energy supply.

## 3. Future energy system design

### 3.1. Energy transition pathways and scenario development

Subject to the features of the local system, three transition pathways sustained by imported electricity, biomass, and N-gas were created. For each pathway, scenarios (including deep decarbonization scenarios and further decarbonization scenarios) were set up every five years from 2016 to 2050 to exhibit the conversion process. The deep decarbonization 2050 scenario of each pathway, as the resulting scenario of all the previous scenarios, was selected as a representation. Further decarbonization scenarios resembled the deep decarbonization scenario, except for the introduction of CCS technology. The crucial assumptions for future scenarios are presented in Supplementary Note 1. A blueprint of the recommended share of energy demand replacement in the energy sectors for each pathway from 2016 to 2050 is provided in Appendix Fig. A1.

*Business-as-usual 2050 scenario*

The business-as-usual (BAU) 2050 scenario resembles the 2016 reference scenario to a large degree, except for updated energy demand, fuel and electricity prices, and technology costs. In addition to the present policy for N-gas utilization, the changes in energy preference and power generation technologies are negligible. It is assumed that the installed capacity of N-gas power plant (PP) units reaches the same level as that of coal-fired units, and all coal-fired boilers and combined heat and power (CHP) plants in the heating sector are replaced by N-gas as fuel by 2050. The BAU 2050 scenario serves as the starting point for evaluation and comparison with other emission reduction scenarios.

*100% electricity 2050 scenario*

The 100% electricity scenario indicates that the remaining energy demand in the energy sector is supported by electricity or alternative energy generated by electricity (e.g. hydrogen). The large electricity demand poses a great challenge to the development of advanced technologies and the future structure of energy sectors, especially the power sector. All the renewable electricity generation technologies (hydropower, wind power, and PV technologies) are added according to their maximum potential. Hydropower (negligible $CO_2$ emissions) from neighbouring provinces (Tibet and Yunnan) is imported when necessary to meet the deviation between local renewable electricity production and total electricity demand.

*Biomass 2050 scenario*

In the biomass transition pathway, the deep decarbonization target is accomplished based on the development and implementation of affiliated bioenergy technologies in all energy sectors. In comparison with other pathways, the changes are moderate in terms of system infrastructure. Renewable electricity technologies are also added to their maximum potential in the biomass 2050 scenario to prevent the future system from utilizing excessive biomass compared with the local potential.

*N-gas 2050 scenario*

Sichuan has great N-gas resources and is experienced in the deployment of corresponding infrastructures (Supplementary Note 2). Given the availability of easy and cost-effective access to N-gas resources in Sichuan, not all renewable electricity technologies are increased to their full potential in this 2050 scenario, and the gap between electricity demand and production can be filled by N-gas PPs. This transition pathway takes N-gas as the main fuel type, and thus a considerable portion of $CO_2$ emissions will remain. Thus, the N-gas scenario cannot reduce the energy-related $CO_2$ emissions to zero.

The main details of the above deep decarbonization scenarios and the corresponding further decarbonization scenarios are summarized in Table 2. The comprehensive parameters of the 2050 scenarios are summarized in Supplementary Table 1.

### 3.2. Energy sectors and key technologies

The design of energy sectors in the future system is determined by the energy-saving level, by the advanced renewable energy technologies, by the maximum electrification degree of energy sector, by the future energy demand forecast (see Method), and the replacement of fossil fuel by different types of energy.

Feasible energy-saving levels in different energy sectors are obtained by investigations and reports on future development trends about energy sectors in China, as well as the related studies focused on the energy-saving potential both here [35] and abroad [36]. Taking into consideration the optimization of existing industrial structure (from heavy industries to high-technology industries in the industrial sector and from low motorization to high-speed vehicles in the transport sector) and the improvement of energy efficiency [37], this study assumes a 30% and 20% reduction of energy demand in the industrial sector and transport sector, respectively. The energy-saving level in the heating and cooling sector, as mentioned in Method, shares the same reduction degree with the industrial sector.

Cross-sectoral technologies build a bridge between the power sector and other energy sectors, for example, heat pump (HP) in the heating and cooling sector and induction furnaces (IF) in the industrial sector.

**Table 3**

Descriptions of the energy sectors in the Sichuan energy system and the key technologies in the energy sectors.

| Energy Sectors | Energy-saving level (%) | Maximum electrification degree (%) | | ELE | BIO | NCS |
|---|---|---|---|---|---|---|
| Heating and cooling sector | 30 | 42.0 | Key technology | IEH, CHP | IEH, CHP | IEH, CHP |
| Industrial sector | 30 | 20.0 | | IFs, hydrogen technology, CCS | | |
| Transport sector | 20 | 58.8 | | EVs, HFCVs | EVs, biofuel vehicles | EVs, HFCVs |
| Power sector | 30 | – | | Hydropower, wind power, PV, CHP, PPs | | |

This provides the probability of converting the fuel demand in other sectors into high-share renewable electricity demand. The maximum electrification degree is thus needed to be determined specific to the energy sector, which is presented in Method in detail. The data indicate the threshold of electricity penetration in each sector, and emphasize the importance of applying cross-sectoral measures in the future system simultaneously.

Further electrification in other energy sectors significantly increases the electricity demand, thus, the power sector is formulated in the end. In the future, it can be estimated that, the energy savings of electricity demand in Sichuan (not include the additional electricity demand by further electrification) will reach 30% in 2050 referring to similar saving potential in foreign regions [38]. Furthermore, to match the balance between the power supply and demand in a renewable energy system in this study, PP and CHP units using novel fuels are considered.

Advanced technologies, along with the order of these technologies, play a vital role in reconstructing the energy sectors of different pathways. For the heating and cooling sector, industrial excess heating (IEH) takes precedence among all heating technologies due to lower investment cost and higher energy efficiency, followed by the HP and finally, the CHP units using different novel fuels specific to the pathway (for example, biomass-fired CHP in BIO pathway). In the industrial sector, IF and similar electrification technologies are responsible for the electrified part. Hydrogen technology contributes to satisfying the rest energy demand together with the alternative energy (biomass or N-gas) in different scenarios, but electrolytic hydrogen technology greatly expands the electricity demand. It may increase the $CO_2$ emission inversely as additional electricity demand can result in more energy consumption (before fulfilling complete renewable power sector). The share of hydrogen energy in the industrial sector differs by scenarios and is further discussed in Supplementary Note 3. For the transport sector, EVs with the vehicle to grid (V2G) technology serve as the first choice to realize the maximum share of electrification as mentioned above. The rest energy demand in heavy-duty transport is supported by various vehicles, for example, the biofuel vehicles in the BIO pathway and the hydrogen fuel cell vehicles (HFCVs) in ELE and NCS pathways.

The design of energy sectors in the future system was determined by the energy-saving level, advanced renewable energy technologies, maximum electrification degree of the energy sector, future energy demand forecast (Section 4), and replacement of fossil fuels with different types of energy.

Feasible energy-saving levels in different energy sectors were obtained by investigations and reports on future development trends in energy sectors in China, as well as related studies focused on the energy-saving potential in China [35] and abroad [36]. Taking into consideration the optimization of existing industrial structures (from heavy industries to high-technology industries in the industrial sector and from low motorization to high-speed vehicles in the transport sector) and the improvement of energy efficiency [37], this study assumed a 30% and 20% reduction in energy demand in the industrial sector and transport sector, respectively. The energy-saving level in the heating and cooling sector, as mentioned in Section 4, had the same reduction degree as the industrial sector.

Cross-sectoral technologies build a bridge between the power sector and other energy sectors, such as heat pumps (HPs) in the heating and cooling sector and induction furnaces (IFs) in the industrial sector. This provides the probability of converting the fuel demand in other sectors into renewable electricity demand. Therefore, the maximum electrification degree specific to the energy sector must be determined, which is presented in detail in Section 4. The data indicate the threshold of electricity penetration in each sector and emphasize the importance of applying cross-sectoral measures in the future system.

Further electrification in other energy sectors significantly increases electricity demand; thus, the power sector was formulated at the end. It was estimated that the energy savings of electricity demand in Sichuan (not including the additional electricity demand by further electrification) will reach 30% by 2050 according to similar saving potential in foreign regions [38]. Furthermore, to balance the power supply and demand in a renewable energy system in this study, PP and CHP units using novel fuels were considered.

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Deep decarbonization scenarios make efforts to decrease the $CO_2$ emissions from energy use. But they are powerless to reduce the $CO_2$ emissions from industrial processes (the estimation method of $CO_2$ emissions from industrial processes is presented in Section 4). Further scenarios consider CCS technology to provide negative $CO_2$ emissions to offset the rest $CO_2$ emissions from the industrial sector, and even the emissions from energy use (in the NCS pathway). The future development prospects of CCS technology are still unclear [39,40] and are further explored in Discussion section. Detailed data on the technology efficiency are summarized in Supplementary Table 2, and the detailed costs of different technologies and system infrastructures are summarized in Supplementary Table 3.

## 4. Method

### 4.1. Modeling tool

The transition towards a deep decarbonization energy system in a province with a fast-growing economy is based on a high share of renewable energy and the implementation of a variety of advanced technologies. As indicated in Section 1, the Smart Energy System

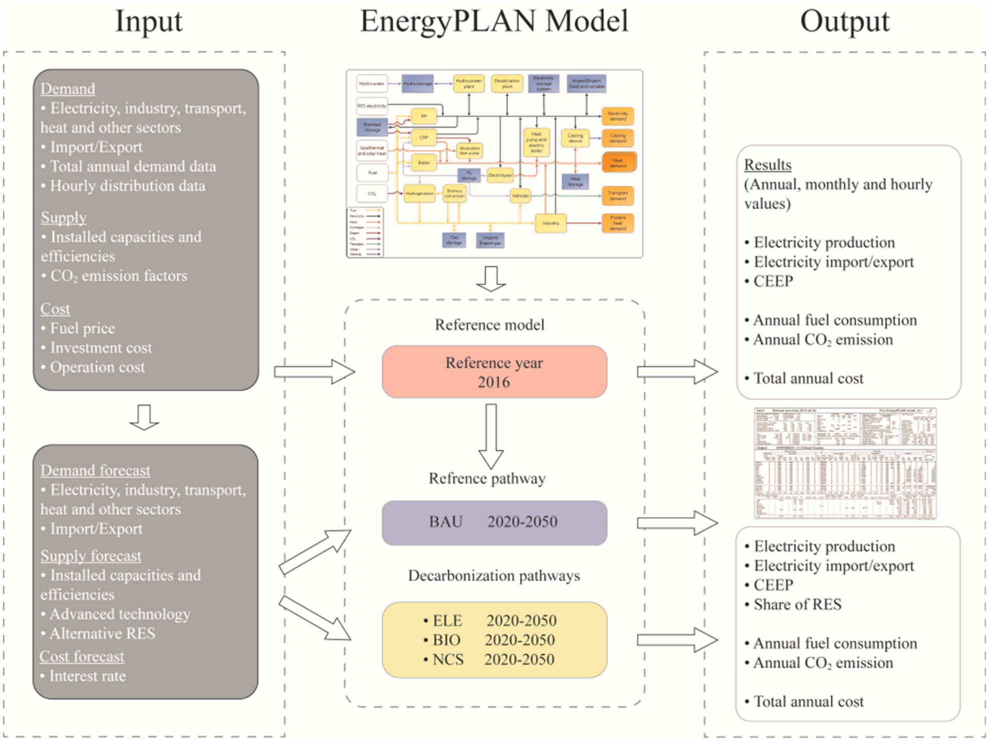

**Fig. 3.** The schematic diagram of the EnergyPLAN model and the structure of the Sichuan analysis.

concept is a key factor contributing to renewable energy integration by merging energy sectors. In addition to the requirement for sector coupling, the optimization tool applied here simulates the Sichuan energy system on an hourly basis for the entire year within the power, heating and cooling, industrial, and transport sectors.

The EnergyPLAN model simulates and optimizes the integration of various intermittent renewable energy sources, the feasibility of various technologies, and the development of energy strategies on a regional or national scale. It can simulate the energy system with all energy sectors (power, heating and cooling, industrial, and transport sectors) on an hourly basis for a whole year. For sector coupling, this simulation tool allows the application of cross-sectoral technologies in energy systems, such as EVs and CHP units. The coupling requirements for energy sectors for different transition pathways are considered in the EnergyPLAN model to improve the energy system efficiency and the benefits of each technology. Thus, it was selected to simulate the pathway towards a deep decarbonization energy system in Sichuan. A schematic diagram of the EnergyPLAN tool and the entire structure of the model for the Sichuan system are shown in Fig. 3.

Extending the conventional energy system parameters, the EnergyPLAN model accounts for the primary energy supply, individual technology cost, aggregated system cost, $CO_2$ emissions, and hourly balance between supply and demand for electricity and heat. Because this tool is a deterministic input/output model using manual heuristics and iterations, it cannot endogenously obtain the optimal energy system configurations, and the results can be obtained in a few seconds [41]. The detailed validation of the EnergyPLAN model and the construction of the Sichuan 2016 reference scenario are presented in Supplementary Tables 4 and 5 and Supplementary Note 4.

### 4.2. *Method for estimating biomass potentials*

The biomass classification method was applied first to define the type of available biomass feedstock in Sichuan, as described in Section 2. The amount of biomass feedstock was then assessed and estimated according to previous studies and reports specific to the biomass feedstock type.

Biomass feedstocks used for biomass production can be divided into five main categories, namely agricultural residues and processing by-products, forestry residues and processing by-products, excrement of living organisms, industrial and domestic sewage, and energy plants. The total biomass potentials were calculated based on the amount of each type of biomass feedstock, as shown in Eq. (1):

$$BP_{Sichuan} = S_A\lambda_1 q_1 + S_F\lambda_2 q_2 + N\lambda_3 q_3 + N\lambda_4 q_4 + Cq_5 \tag{1}$$

where $BP_{Sichuan}$ refers to the annual total biomass potentials in Sichuan; $S_A$ and $S_F$ represent the area of agricultural land and forest land in Sichuan, respectively; N refers to the total population in Sichuan; C is the number of energy plants in Sichuan; Î»$_i$ represent the amount of biomass feedstock i per unit; and $q_i$ refers to the calorific value, which is the heat value produced per physical unit of biomass feedstock i.

For the former four types of biomass feedstocks, few data contribute to directly calculating the precise amount of raw materials in Sichuan, and the biomass reports in the neighboring region are used to indirectly determine the amount. Hunan, a neighbouring province similar to Sichuan in latitude range, climatic conditions, and living standards, was chosen as an alternative to collect per unit data on biomass feedstocks. According to the 13th Five-Year Plan for the development of biomass in Hunan [42], the annual amount of agricultural residues available throughout the province in 2016 was equivalent to 40 million tons, while the amount of forestry residues was equivalent to 37 million tons (Supplementary Table 6). Given that Sichuan and Hunan produce the same amount of domestic sewage per capita and have the same quality of agricultural and forestry residues per hectare, the estimation of agricultural and forestry residues in Sichuan as well as the amount of excrement of living organisms and industrial and domestic sewage can be calculated subject to a linear relationship. The resulting amount of each type of biomass feedstock was then aggregated to determine the total biomass potential in Sichuan in 2016.

The estimated amount of biomass produced until 2050 was determined based on the biomass potential in 2016. For agricultural and forestry residues and processing by-products, the variation of these two types of biomass feedstocks mainly depends on the increase or decrease in agricultural and forestry land, which was assumed to be similar to the level in 2016 in this study. The excrement of living organisms and industrial and domestic sewage are strongly influenced by both the population and living standards. The quantity of raw materials is expected to moderately increase according to future population prospects and the improvement of living standards in Sichuan. The widespread cultivation of plants developed specifically for energy use rather than for food will be a key factor affecting the rapid increase in biomass in the future. However, the estimated expansion of biomass potential by energy plants differs across studies. Given information on suitable high-yield energy crops and available marginal land, the biomass potential range was determined based on a literature review, as shown in Supplementary Table 7. Sichuan must ensure food security in the developing country as a major agricultural province [43]. This study considered only marginal land and valley areas for energy plant cultivation in the future, and conservatively estimated that Sichuan will obtain 115 TWh of bioenergy from energy plants. The detailed projections for the aggregated biomass potentials in Sichuan are presented in Supplementary Note 5.

### 4.3. *Method for forecasting energy demand*

The energy demand of different energy sectors could have an important influence on the design of future systems in Sichuan. The local economic growth rate is closely linked to the primary energy consumption of the energy sector, which is crucial for forecasting future energy demand. As in ref. [44], the average annual rate of increase in GDP in Sichuan was estimated to be approximately 5% in the middle term of 2020–2035 and approximately 2% in the long term of 2035–2050. Based on data on the rates of increase in GDP and energy demand of energy sectors (heating and cooling, industrial, and transport sectors) in 2016, a method for forecasting future energy demand was adopted to schedule energy sectors in the future system. Combined with the adjustment and upgrading of industrial structures, this method assumes that the ascending trend of energy demand is consistent with that of GDP, but the specific growth rate differs by sector. The detailed energy demand variations of the energy sectors from 2016 to 2050 are provided in Supplementary Fig. 1.

### 4.4. *Method for determining the electrification degree in future sectors*

*Heating and cooling sector* The climate of the Sichuan Basin is typically a subtropical monsoon climate (warm and moist throughout the year). The present policy in Sichuan does not include district heating, and nearly all the individual heat demand is supplied by ventilators and air conditioners [45]. This means that all the heat demand comes from the industrial sector.

In the absence of actual data on the heat demand of each industrial sub-sector in Sichuan, information on all the industrial products in Sichuan and the total heat demand of Chinese industry was collected to estimate the heat demand of each industrial sub-sector, as shown in Eq. (2):

$$HD_{Sichuan-i} = HD_{Sichuan}\left(\frac{HD_{China-i}\left(\frac{P_{Sichuan-i}}{P_{China-i}}\right)}{\sum_{i=1}^{39} HD_{China-i}\left(\frac{P_{Sichuan-i}}{P_{China-i}}\right)}\right) \tag{2}$$

where $HD_{Sichuan-i}$ refers to the heat demand of industrial sub-sector i in Sichuan; $HD_{Sichuan}$ represents the total heat demand in Sichuan; $HD_{China-i}$ refers to the heat demand of industrial sub-sector i in China; $P_{Sichuan-i}$ is the number of products in industrial sub-sector i in Sichuan, and $P_{China-i}$ is the number of products in industrial sub-sector i in China. There are 39 industrial sub-sectors in the Chinese industry and the results on the heat demand of each industrial sub-sector in Sichuan are shown in Supplementary Table 8.

The heat demand distinguishing method was implemented to define the type of heat demand from the industrial sector. Based on correlation studies, industrial heat demand can be divided into two categories, namely low-temperature and high-temperature heat demand. Space heating and process heating below 100 °C during the industrial process are regarded as low-temperature heat demand, whereas the remaining heating is high-temperature heat demand. Because low-temperature heat demand can be satisfied by HPs and IEH, this part of the heat demand is considered to be capable of further electrification. Moreover, this study presumes that the heat demand of heavy industrial sub-sectors (such as iron and steel manufacturing, cement and ceramic manufacturing, and metal mining and processing industries) are classified as 90% high-temperature heat demand and 10% low-temperature heat demand, and the heat demand of light industrial sub-sectors (such as food and beverage manufacturing and paper and paper pulp industries) are classified as low-temperature heat demand, as shown in Eq. (3):

$$\alpha_{electrification} = \frac{0.1 \cdot HD_{Sichuan-j} + HD_{Sichuan-k}}{HD_{Sichuan}} \tag{3}$$

where Î ± $_{electrification}$ refers to the maximum electrification degree in the heating and cooling sector in Sichuan;$HD_{Sichuan}$ represents the total heat demand in Sichuan;$HD_{Sichuan-j}$ refers to the heat demand of light industrial sub-sector j in Sichuan, and$HD_{Sichuan-k}$ refers to the heat demand of heavy industrial sub-sector k in Sichuan. According to the above data and assumptions, the electrification degree in the heating and cooling sectors was obtained using this method, as provided in Supplementary Note 6.

*Industrial sector* Owing to the diversity of industrial sub-sectors in Sichuan and the significant electricity demand in the industrial sector, the electrification degree of the industrial sector was ascertained based on previous research and reports rather than on a method. In this study, the proportion of electrification in the industrial sector was fixed at 20% of the energy demand (after energy saving) according to the similar electrification potentials reported in previous studies.

*Transport sector* Similar to the method in the heating and cooling sector, the chief transport mode in Sichuan was divided into four types, namely road, waterway, railway, and air transport. According to the objects contained, they can be classified as passenger transport and freight transport. The passenger and freight turnover of these four major transport modes in 2016 are listed in Supplementary Table 9. For road transport, which consumes the largest amount of energy in the transport sector, this study divided passenger cars into three categories (large/medium/small) and trucks into three categories (heavy/medium/light). The electrification degree in road transport was calculated assuming that only medium and small passenger cars and light trucks can be replaced by EVs based on the proportion of different types of passenger cars and trucks in Sichuan (Supplementary Tables 10, 11 and 12). For the other three transport modes, it is recognized that most heavy-duty transport (waterway, railway, and air transport) vehicles cannot be supported by electricity, and thus the energy demand cannot be electrified. Using this method, the share of electrification in the transport sector was determined and is presented in Supplementary Note 7.

### 4.5. *Method for estimating the $CO_2$ emissions from industrial process*

In addition to the reduction of $CO_2$ emissions from energy use, this study also accounted for the emissions from industrial processes in further decarbonization scenarios to achieve zero direct emissions. The $CO_2$ emissions from industrial processes (mainly in the chemical, nonmetal ore mining, and non-ferrous metal smelting industries) are responsible for approximately 14% of the total emissions in the industrial sector [46]. However, this share of $CO_2$ emissions is expected to increase slowly in the future in China. $CO_2$ emissions from industrial processes largely depend on the scale of industrial production and the amount of specific industrial products. Thus, assuming that the $CO_2$

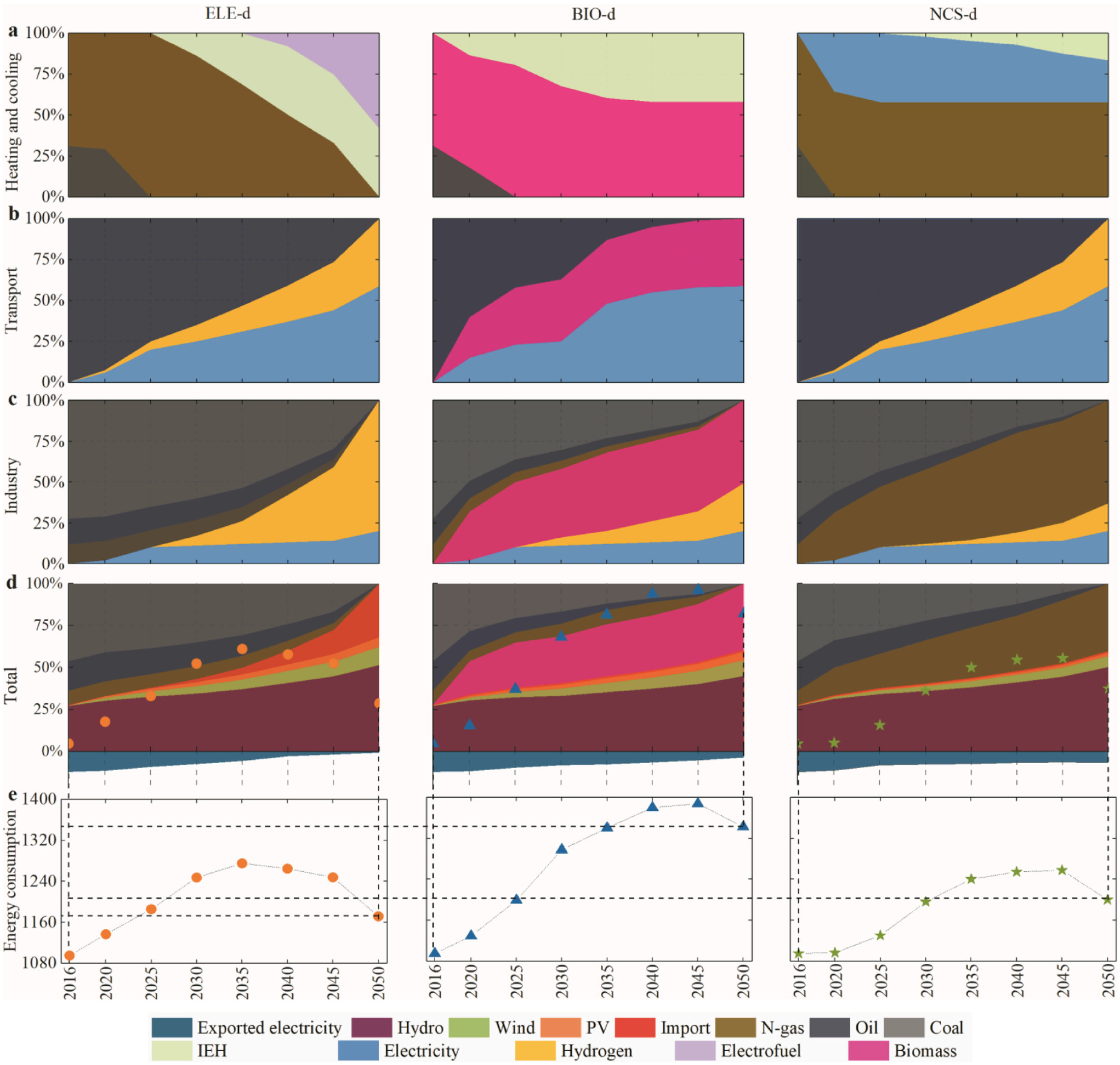

**Fig. 4.** Primary energy supply for each sector and the entire energy system in the three transition pathways from 2016 to 2050. **a** Primary energy supply of heat sector in the three transition pathways. **b** Primary energy supply of the transport sector in the three transition pathways. **c** Primary energy supply of the industrial sector in the three transition pathways. **d** Primary energy supply of the entire energy system in the three transition pathways. **e** Absolute value of energy consumption in the total energy system (all units in TWh). The positive and negative values on the coordinate axis of the total energy system (**d**) represent the energy consumption and output in the region, respectively. In this study, the energy output from Sichuan mainly focused on the exported hydropower, as shown in the negative half axle of the total energy system (**d**).

emissions from industrial processes are proportional to the total $CO_2$ emissions of the industrial sector, this share of $CO_2$ emissions can be estimated based on the energy-related $CO_2$ emissions before energy saving and further electrification (a representation of the scale of industrial production), as shown in Eq. (4):

$$CEI_n = \frac{\eta}{1-\eta} CEE_n \tag{4}$$

where CEI$_n$ refers to the $CO_2$ emissions from industrial processes of the industrial sector in year $n$;CEE$_{BAU\text{-}n}$ represents the $CO_2$ emissions from energy use of the industrial sector in year $n$; and η refers to the share of $CO_2$ emissions from industrial processes in the total $CO_2$ emissions in the industrial sector before energy saving and further electrification, which is set to 10% in this study considering the current situation of the industrial sector in Sichuan province. After determining the total energy demand of the industrial sector before energy saving, the $CO_2$ emissions from industrial processes were obtained according to Eq. (4). The $CO_2$ emissions from industrial processes in all scenarios (including the BAU scenario and decarbonization scenarios) were the same in one year.

**Table 4**
Exported and imported electricity, and the energy self-sufficiency level for the bau 2050 scenario and other decarbonization scenarios of three pathways.

| | BAU | ELE-d | BIO-d | NCS-d | ELE-z | BIO-z | NCS-z |
|---|---|---|---|---|---|---|---|
| Exported electricity (TWh/y) | 295.50 | 5.52 | 46.59 | 77.49 | 5.10 | 45.54 | 46.42 |
| Imported electricity (TWh/y) | 12.27[a] | 389.41 | 12.76 | 12.78 | 399.00 | 12.77 | 12.98 |
| Energy self-sufficiency level (%) | 99.99 | 67.23 | 99.99 | 99.99 | 66.67 | 99.99 | 99.99 |

[a] The ratio of fixed imported electricity in 2050 is assumed to maintain the same ratio of imported electricity to total electricity demand as in 2016.

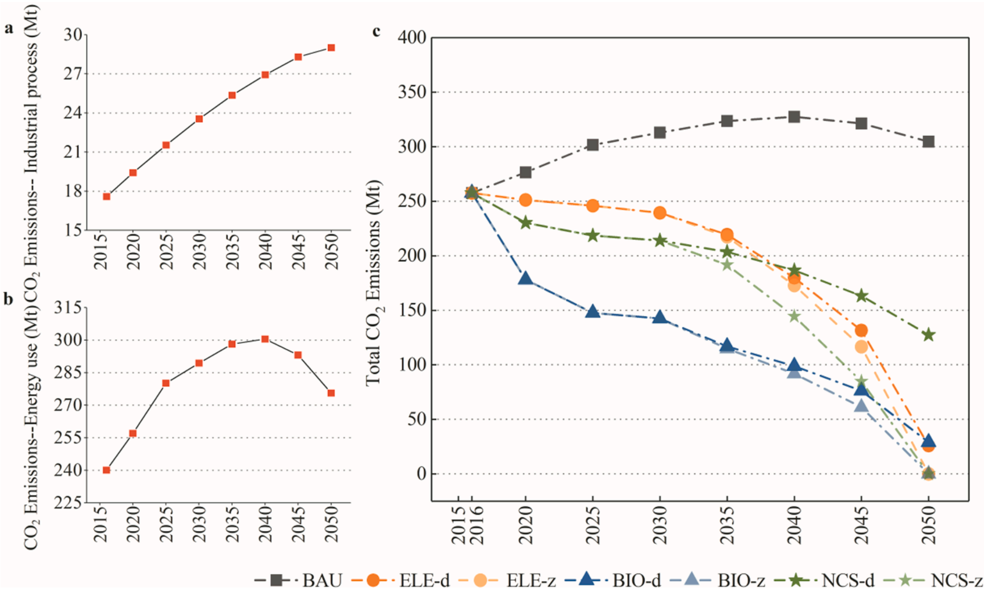

**Fig. 5.** CO$_2$ emissions of the BAU and the deep decarbonization and further decarbonization scenarios of the three transition pathways from 2016 to 2050. **a** CO$_2$ emissions from industrial processes. **b** CO$_2$ emissions from energy use in the BAU scenario **c** Total CO$_2$ emissions of the BAU, deep decarbonization and further decarbonization scenarios of the three transition pathways. The color indicates the pathway.

## 5. Results

### 5.1. Energy self-sufficiency

The indicator energy self-sufficiency was applied to assess the capability of different transition pathways to meet the future energy demands for local energy resources. The variation of the primary energy supply in each sector and the total system for deep decarbonization scenarios from 2016 to 2050 is illustrated in Fig. 4. The imported and exported electricity, as well as the energy self-sufficiency level in scenarios of different pathways, are presented in Table 4. As renewable electricity replaced thermal conversion technologies and efficient substitutional energy replaced fossil energy in traditional industries, the energy consumption in all decarbonization scenarios significantly decreased compared with that in the BAU scenario (1626 TWh). The share of alternative energy in each pathway, together with renewable electricity, gradually increased and reached 100% in 2050. The imported electricity in ELE-d was considered alternative energy and increased to 389.41 TWh/y (equal to 32.8% of the primary energy supply). The demand for biomass and N-gas improved significantly in the other two scenarios compared with the highest efficiency of the 100% electric energy system (Fig. 4e), and reached 530.0 TWh/y (equal to 39.5% in scenario BIO-d) and 482.6 TWh/y (equal to 40.2% in scenario NCS-d), respectively.

Scenarios ELE-d and ELE-z, although adding all the renewable electricity technologies to maximum potential, exported a negligible amount of electricity and had an energy self-sufficiency rate of less than 68%. The introduction of CCS technology only decreased the self-efficiency rate by 0.56% (Table 4). The biomass potential and N-gas production in Sichuan in 2050 remained within the energy potential and realized the goal of deep decarbonization. Thus, the energy self-sufficiency rate of these two scenarios was nearly 100%, and CCS technology implementation in these two pathways had little impact.

Hydrogen technologies, which utilize additional electricity with more storage opportunities, serve as one of the most important measures to improve energy self-sufficiency in emission reduction scenarios. This measure offers a major opportunity to diminish and convert the exported electricity to produce hydrogen to satisfy energy demand, and thus decreases the need for alternative energy (biomass or N-gas). Scenario NCS-d under island mode (no interconnection capacity) in Sichuan was developed to evaluate the impact of this measure on energy self-sufficiency, and is detailed in Supplementary Note 8 and Supplementary Fig. 2.

**Table 5**
CO$_2$ Emission reduction percent of different pathways from 2020 to 2050.

| Pathways | CO$_2$ emission reduction percent (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
| ELE-d | 9.15 | 18.50 | 23.50 | 32.18 | 45.10 | 59.08 | 91.52 |
| BIO-d | 35.61 | 51.06 | 54.45 | 63.89 | 69.83 | 76.30 | 90.48 |
| NCS-d | 16.72 | 27.57 | 31.61 | 37.07 | 43.00 | 49.24 | 58.17 |
| ELE-z | 9.15 | 18.50 | 23.50 | 32.80 | 47.24 | 63.75 | 100.00 |
| BIO-z | 35.61 | 51.06 | 54.45 | 64.50 | 71.96 | 80.97 | 100.00 |
| NCS-z | 16.72 | 27.57 | 31.61 | 40.77 | 55.88 | 73.61 | 100.00 |

### 5.2. Environmental sustainability

The annual CO$_2$ emissions of the three transition pathways and the reference pathway from 2016 to 2050 are shown in Fig. 5. As a reference, the CO$_2$ emissions of the Sichuan energy system are likely to peak around 2040 (between 320 Mt CO$_2$ and 330 Mt CO$_2$) and decrease to approximately 304 Mt CO$_2$ by 2050, including CO$_2$ emissions from energy use (Fig. 5b) and industrial processes (Fig. 5a). The emission reduction level differed by deep decarbonization 2050 scenario with 91.52% for ELE-d, 90.48% for BIO-d, and 58.17% for NCS-d. This is mainly due to the existence of industrial process emissions. With the implementation of CCS technology, all further decarbonization scenarios will achieve the zero direct CO$_2$ emission target in 2050.

CO$_2$ emissions in scenario NCS-z declined slowly at the earlier stage compared with that in scenario NCS-d, but began to rapidly decrease owing to the large introduction of CCS technology in 2030. The BIO pathways (BIO-d and BIO-z) maintained a relatively low emission level throughout the projected period based on extensive biomass utilization. The CO$_2$ emission reduction percentages of the different pathways are listed in Table 5. The CO$_2$ emission reductions contributed by each implementation measure in these 2050 scenarios are presented in Supplementary Note 9 and Supplementary Fig. 3.

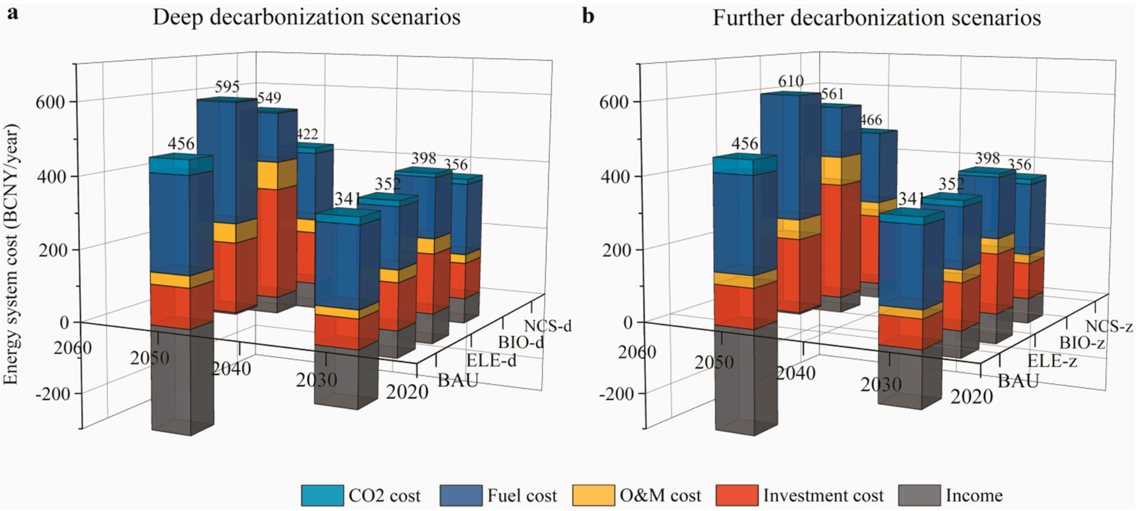

**Fig. 6.** Total energy system costs of the reference and three transition pathways in 2030 and 2050. **a** Total energy system costs of the BAU and the deep decarbonization scenario of these three pathways. **b** Total energy system costs of the BAU and the further decarbonization scenarios of these three pathways.

**Table 6**

The effect of ccs technology introduction in investment cost by pathway.

| Pathways | Investment cost (BCNY) | | Difference (%) |
|---|---|---|---|
| | Deep decarbonization (-d) | Further decarbonization (-z) | |
| ELE | 198.2 | 208.4 | 5.15 |
| BIO | 320.6 | 333.9 | 4.15 |
| NCS | 159.1 | 210 | 31.99 |

### 5.3. *Economic affordability*

To assess the economic feasibility of establishing a deep decarbonization system in a rapidly developing region, the total energy system costs of these decarbonization scenarios in 2030 and 2050 are shown in Fig. 6. The key assumptions regarding the fuel prices and fuel handling costs are summarized in Supplementary Tables 13 and 14. In 2030, owing to the increasing investment costs of the ELE and BIO pathways and the fuel costs of the NCS pathways, the energy system costs of all the decarbonization scenarios were high compared with those of the BAU scenario. The highest system costs appeared in the BIO scenarios, accounting for 398 BCNY/y (approximately 1.17 times greater than that of the BAU scenario). Furthermore, the revenue from electricity in the transition scenario was significantly lower because large-scale electrification in the decarbonization scenarios led to a considerable decline in exported electricity.

The energy system cost of the BAU scenario in 2050 was 456 BCNY/y, whereas the revenue from electricity sales reached 293 BCNY/y. Unlike the system costs in 2030, the highest system costs occurred in scenario ELE-d among all the deep decarbonization scenarios, which was approximately 1.3 times greater than that of the BAU scenario. This was attributed to the high fuel cost (i.e. the cost of imported electricity) and investment cost, which accounted for 56.8% and 33.3% of the total cost, respectively. In particular, the system cost of scenario NCS-d was lower than that of the BAU scenario because the fuel cost savings was larger than the expansion of investment cost; however, the revenue from electricity sales in scenario NCS-d was only 25.9% of the revenue of the BAU scenario owing to the decrease in exported electricity.

Even when considering zero $CO_2$ costs, all the further decarbonization scenarios induced cost accumulation. In particular, scenario ELE-z had the highest energy system cost, increasing to 610 BCNY/y with negligible income. The introduction of CCS technology was the main factor influencing the system costs of scenarios ELE-z, BIO-z, and NCS-z compared with the deep decarbonization scenarios, contributing to increases of 2.5%, 2.7%, and 10.4%, respectively. In addition, the effect of CCS technology implementation on investment cost between the deep decarbonization and the further decarbonization scenario is provided in Table 6. The highest investment cost expansion occurred in the NCS-z scenario, accounting for nearly 32% of the total investment cost, while the investment cost expansion in the ELE-z and BIO-z scenarios was responsible for 5.15% and 4.15%, respectively. Differences appeared between the further decarbonization scenarios in the investment cost expansion owing to different factors for scenarios (i.e. the significant demand for interconnection and the electrolyser capacity in scenario ELE-z, biofuel technologies in scenario BIO-z, and extensive utilization of CCS technology in scenario NCS-z). The forecasted cost of advanced technologies may significantly decrease owing to further development in the future, which will make the cost of a deep decarbonization energy system lower than forecasted.

**Table 7**

The total system costs and the source of highest system costs of all scenarios.

| Scenarios | Total system costs (BCNY) | Highest cost source | Highest system costs (BCNY) | % of total system costs |
|---|---|---|---|---|
| BAU | 456 | Fuel cost | 268 | 58.86 |
| ELE-d | 595 | Fuel cost | 338 | 56.85 |
| BIO-d | 549 | Investment cost | 321 | 58.43 |
| NCS-d | 422 | Fuel cost | 205 | 48.62 |
| ELE-z | 610 | Fuel cost | 346 | 56.75 |
| BIO-z | 561 | Investment cost | 334 | 59.56 |
| NCS-z | 466 | Fuel cost | 213 | 45.79 |

Regarding the largest source of the system costs, it is the investment cost in the BIO-d and BIO-z scenarios and fuel cost in all other future scenarios. The largest sources of the system cost in all scenarios are presented in Table 7.

Considering the related research on the cost of renewable energy systems (3.2 CNY/person•TWh) in Chinese provinces in the future [44], the total cost of establishing a decarbonization energy system in Sichuan (4.53–6.09 CNY/person•TWh) is expected to remain at a similar level to that of the comparable renewable system in 2050.

Sensitivity analyses of the system cost results for different interest rates and electricity prices in the further decarbonization scenarios are summarized in Fig. 7. Two real interest rates, namely 4% (Fig. 7a) and 8% (Fig. 7b), were employed to calculate the energy system cost. In

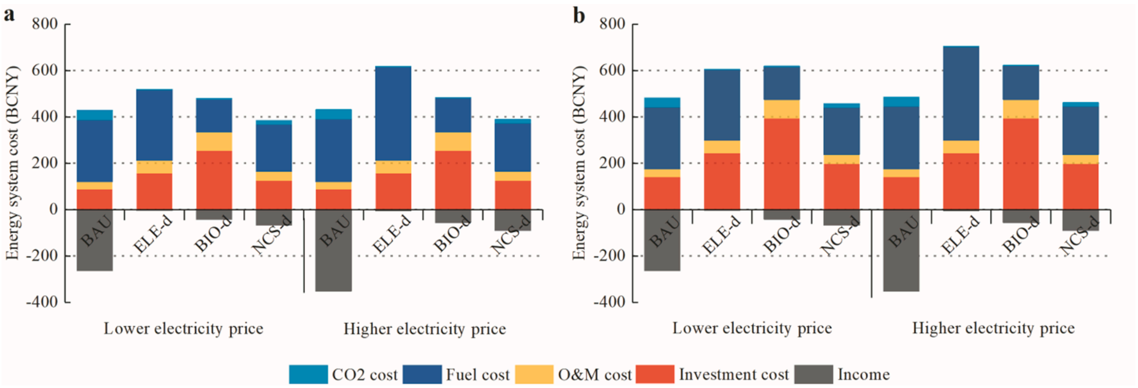

**Fig. 7.** Sensitivity analyses of system cost results for different interest rates and electricity prices in deep decarbonization (-d) scenarios. **a** Total energy system cost in 2050 at different electricity prices, using a real interest rate of 4%. **b** Total energy system cost in 2050 at a different electricity prices, using a real interest rate of 8%.

addition, two levels of electricity prices in 2050 were utilized to evaluate the impact of electricity prices. The higher electricity price means it increases by 1.2 times compared with the original price, whereas the lower price is 0.9 times lower. The interest rate had a significant effect on the investment costs in all scenarios. Lowering the interest rate to 4.0% instead of 6.0% in the BAU scenario decreased the annual system cost by 5.6%, whereas increasing the interest rate to 8.0% increased the annual system cost by 6.1%. In scenario BIO-d, a 4.0% interest rate curtailed the annual system costs by 12.2%, whereas an 8.0% interest rate increased the annual system costs by 13.3%. Compared with other scenarios, scenario BIO-d showed a greater reaction to the change in interest rate because the BIO pathway requires more investment. The fluctuation in electricity price had a great impact on the fuel costs and electricity sales revenue in all scenarios, particularly scenario ELE-d. Considering the uncertainty of future electricity prices, the BIO and NCS pathways seem to be more economically beneficial than the ELE pathway if there are higher electricity prices in 2050.

Given information on the $CO_2$ emission reduction potential and energy system costs of these transition pathways, the $CO_2$ abatement costs of the further decarbonization scenarios are presented in Supplementary Note 10 and Supplementary Fig. 4.

## 6. Discussion

The establishment of a deep decarbonization energy system in the future depends largely on the utilization of biomass. Therefore, a biomass pathway in Sichuan was proposed to evaluate the effect of bioenergy. However, whether the biogenic carbon neutrality principle can be applied throughout its life cycle is controversial in academia [47,48] and poses a hurdle for the accounting of $CO_2$ emissions. In this study, it was assumed that all forms of bioenergy abide by the principle of carbon neutrality when the availability of biomass feedstocks is restricted to Sichuan.

These three transition pathways are extreme because the remaining energy demand in sectors is satisfied by a single energy type or technology. This is impractical in an actual system. A combination of these alternative energies is more likely to occur. This design aims to demonstrate which pathway is more suitable for the transition to deep decarbonization of the Sichuan energy system in the future. The renewable transition pathways are evaluated from three perspectives: energy self-sufficiency, environmental sustainability and economic affordability. They serve as the key factors influencing which is the optimal pathway. This study confirmed that all the 2050 scenarios are technically feasible to realize deep decarbonization of the energy system in Sichuan. In deep decarbonization scenarios, the BIO pathway performs better than the NCS pathway in emission reduction. The ELE pathway has the highest emission reduction percent among all transition pathways. However, the energy self-sufficient level of the ELE pathway far below the other two pathways, and the system cost of the ELE pathway is the highest. Thus, the BIO pathway is considered the most suitable pathway in deep decarbonization scenarios. As for further decarbonization scenarios, the emission reduction percent of the NCS pathway improves to 100% due to the introduction of CCS technology. Therefore, the NCS pathway is considered the most cost-effective one in achieving “zero-emission”. However, the last-step technology (i.e. CCS) in reducing the rest $CO_2$ emissions has not been fully commercialized. Uncertainties exist in considering this scenario as the most cost-effective in Sichuan. CCS technology owns special significance in achieving the “zero-emission” goal in Sichuan, and China. If CCS technology is not considered in China in the future, then some emissions unrelated to energy use will not be eliminated or offset by currently visible technology. In addition, many carbon capture demonstration projects had been put into operation [49] and studies do exist in presenting a positive attitude in the CCS technology commercialization in China [40,50]. CCS technology is thus considered to play an indispensable role in future deep decarbonization. In this study, the highest cost expansion brought by CCS technology implementation occurred in the NCS-z scenario, accounting for approximately 44 BCNY/y (9.4% of the total energy system cost).

Although the energy system costs were predicted to remain at an acceptable level in Sichuan, those of all the renewable transition pathways were higher compared with those of the BAU scenario either because of the additional investment cost or because of the decreasing electricity sales revenue. The investment cost was responsible for a large share of the energy system cost (40–60%) in further decarbonization scenarios owing to the large installed capacities of renewable technologies, especially emerging technologies such as electrolyser and biofuel plants. It is difficult to forecast the costs of these renewable technologies until 2050. The rapid development of technology may greatly decrease the costs applied in this study because the total system cost is expected to decrease faster than the projection and alleviate economic pressure for a deep decarbonization system. Thus, incentives should be introduced in Sichuan as soon as possible to accelerate the improvement and commercialization of advanced technologies. Policy decisions and public management measures, such as the current deployment of CHP plants and CCS technology [49], are needed to provide such incentives.

Energy-efficiency measures and a cross-sectoral approach will serve as the foundation of future decarbonization systems. After introducing advanced storage solutions in the transport sector, the electricity storage capacity will still play a vital role in a large energy system with a high proportion of hydropower. It will enable alternative energy-saving and energy efficiency improvements by taking advantage of excess electricity in the power sector. A more ambitious plan for electricity storage with an emphasis on seasonal regulation capacity will be crucial for realizing future deep decarbonization of the Sichuan system. A reservoir power station with seasonal regulation capacity is regarded as the best

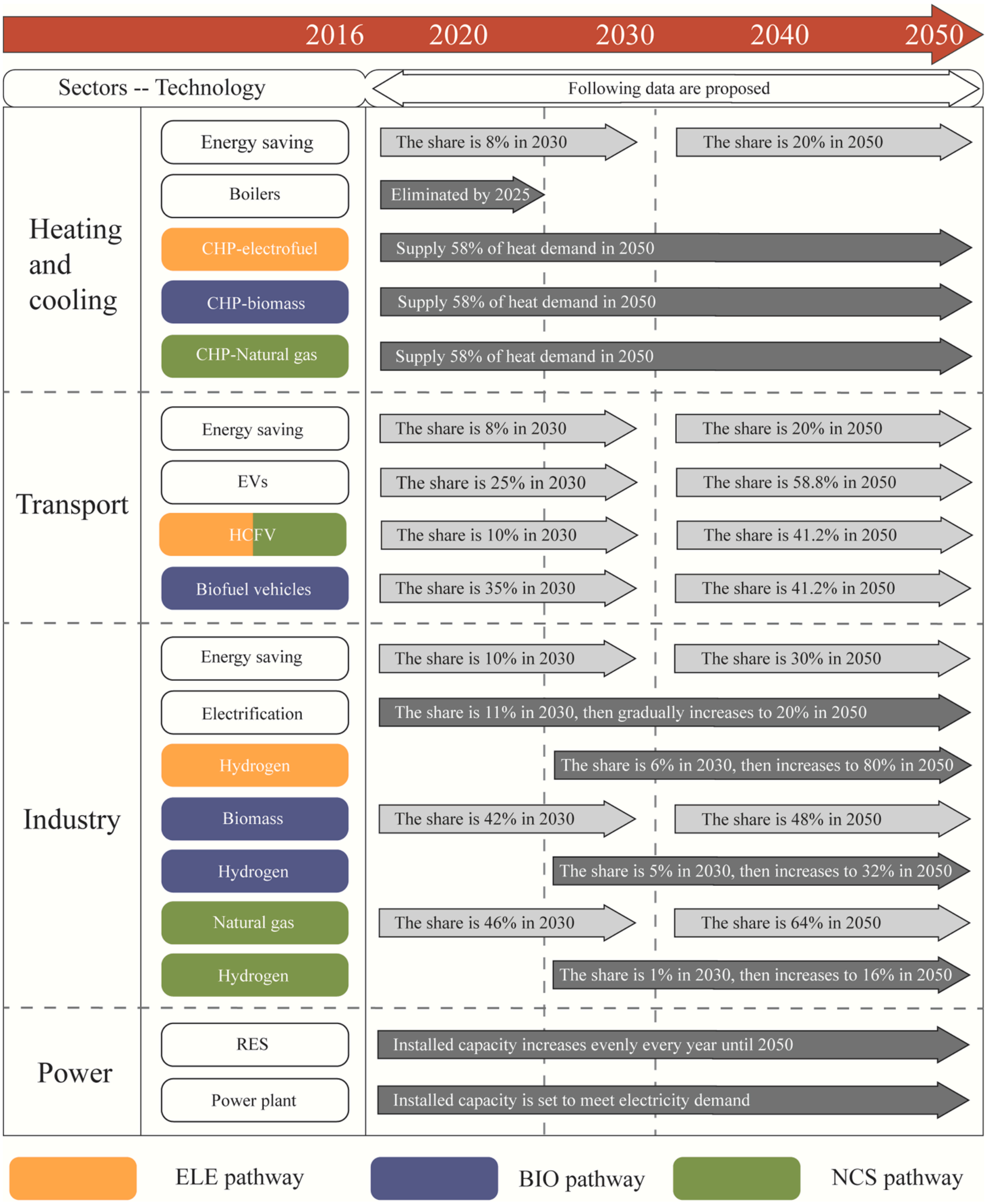

**Fig. A1.** Blueprint of the share of energy demand replacement in energy sectors for the three transition pathways. The recommended share of energy demand replacement in different energy sectors (heating and cooling, industrial, transport and power sectors) for three transition pathways (ELE, BIO and NCS) from 2016 to 2050. Deep decarbonization (-d) and further decarbonization (-z) scenarios are all developed based on the above-recommended shares in all energy sectors.

choice to expand the electricity storage capacity in Sichuan, but the current goal for construction of reservoir power stations, i.e. 1.1 GW by 2020 [50], underestimates such importance.

In the analysis, the future system design proposed for the deep decarbonization system in Sichuan was developed on the basis of comprehensive data, and methods for estimating energy demand and determining the maximum electrification degree were proposed. Some of the designs were implemented only in the Sichuan energy system, such as the GDP increase rate and the ratios of different types of heat demand and vehicles. Despite these differences, most of the design can contribute to building a deep decarbonization energy system or even a zero $CO_2$ emission system in other provinces in China. This study provides methodology for constructing a future deep decarbonization energy system in China. Based on the gathered data and similar policies in the same country, the methods are suitable for application in other Chinese regions. In particular, the predicted results of achieving a deep decarbonization energy system in one area of China are presented for the first time, and indicate that it is feasible to convert the energy system of one of the most rapidly developing regions in China into a deep decarbonization system from both technical and economic perspectives. This will likely induce more focus on the deep decarbonization energy system and lead to more attempts in neighboring provinces facing a similar conflict between economic development and carbon emissions. Considering future economic growth and technological development in China, deep decarbonization and carbon neutralization goals may become more desirable and serve as vital choices for provincial regions to mitigate $CO_2$ emissions and finally reach the national emission target.

## 7. Conclusion

Reducing $CO_2$ emissions is an essential target in future energy system transitions, especially in China. This study explored the feasibility of achieving deep decarbonization in the Sichuan energy system, which is one of the leading provinces in economic growth in China. Three transition pathways were designed with the local hydro, wind and PV resources are employed first. The difference is that the rest of energy demand is supported by imported electricity, biomass, and natural gas, respectively. Moreover, deep decarbonization and further decarbonization scenarios were developed in each of the three pathways, the main difference lies in the inclusion of CCS technology. The EnergyPLAN tool was used to conduct an hourly simulation of the entire energy system including all energy sectors (heating and cooling sector, industrial sector, transport sector and power sector).

The results indicate that it is technically feasible to deeply decarbonize the energy system of one of the most rapidly developing regions in China based on existing technologies. As for the primary energy supply, the energy self-sufficiency rate of the 100% electricity pathway was less than 68% in both the deep and further decarbonization scenarios. The difference between deep and further decarbonization scenarios in energy supply was limited in the other two pathways. Their energy self-sufficiency rates reached nearly 100%. Meanwhile, the total energy system cost peaked in the further decarbonization scenario in the 100% electricity pathway (equal to 610 BCNY/y, i.e. 1.3 times greater than that of the reference system) and was the lowest in the N-gas pathway (1.02 times of the reference system). In addition, the costs of all the decarbonization 2050 scenarios in the future Sichuan province were similar to that of the comparable provincial renewable systems in China.

This study contributes to formulating region-specific $CO_2$ mitigation strategies for policymakers, and is expected to be of great help in the establishment of deep decarbonization energy systems in areas facing the greatest conflict between economic development and carbon emissions. More importantly, the methods and results of constructing a deep decarbonization energy system in this study could also be applied in other regions, which are not limited to specific countries.

## 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.

## Acknowledgments

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## Appendix A. Blueprint of the share of energy demand replacement in energy sectors for three transition pathways.

See Fig. A1.

## Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117507.

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