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Decarbonization of China's electricity systems with hydropower penetration and pumped-hydro storage: Comparing the policies with a techno-economic analysis

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A B S T R A C T

Hydropower has a key role to play in achieving carbon neutrality targets. However, the rapid development of hydropower plants and the slowdown in the growth of electricity demand can easily cause imbalances in the energy system. Therefore, this study explores the possibility of achieving deep decarbonization by 2030 in a region which has a high installed hydropower capacity and proposes solutions to the problems of water abandonment and supply-demand imbalance. This is done by developing various models and pathways to meet the electricity, industry, and transportation energy demands in Sichuan Province, China within the confinement of the government policies. Hence, three different scenarios including reference scenarios, policy scenarios, and optimization scenarios are modeled. These scenarios consider the resource development potential of renewable energy, energy policies, and the development of advanced technologies. Under different hydropower generation capacities, hybrid hydropower-photovoltaic-wind-biomass energy systems are constructed using the EnergyPLAN model, and the planning models for a clean/zero-carbon energy system in 2030 are proposed. Results from the analysis of the models showed that the conservative policy models could reduce CO2 emissions to some extent. Decarbonization models with different levels of hydropower generation under different scenarios could all result in zero CO2 emissions. The large-scale use of energy storage results in a significant increase in investment costs, but a significant reduction in energy costs. The results of this study validate the possibility of achieving decarbonization in areas with high hydropower potential. This also suggests the best decarbonization model for meeting the different needs of the future energy system. This article provides a reference and basis for any province or region to achieve long-term decarbonization using hydropower.

1. Introduction

The increasing energy demand and complex energy structure led to the rapid growth of primary energy consumption. In 2018, global primary energy consumption grew by 2.9%, which is almost twice the average annual growth rate over the decade (and the fastest since 2010). Meanwhile, carbon emissions increased by 2.0% (the fastest growth in seven years) [1]. To a large extent, the growth of carbon emissions can be associated with an increase in energy growth. Renewable energy (RE) sources such as hydro, wind, solar, biomass, etc. have become the developmental direction that is advocated for by many countries [2]. With changing energy consumption patterns and demand-side structures, China is one of the world's largest contributors to energy growth. This country has also become an important driver of the global clean energy transition [3]. However, due to the complicated Chinese geographical environment/energy structure, the replacement of coal/oil with gas/electricity and increasing the installed capacity of RE systems may

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Nomenclature

PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy system
V2G	Vehicle-to-grid
O&M	Operation and Maintenance
Hydro	River hydropower plant
CCS	Carbon sequestration
ESS	Energy storage systems
HSPSI	Hydropower station with pumped-storage installation
REF	Reference scenario
PES	Primary energy source
CEEP	Critical excess electricity production
EEEP	Exportable excess electricity production
EV	Electric vehicle
IMP	The import model
ESM	The energy storage model

not be suitable for the country's long-term development [4].

Researchers have presented the construction of decarbonized power systems at regional and national levels and proposed various novel technologies/algorithms. To achieve greenhouse gas emission reduction goals, Vaillancourt et al. [8] found that three fundamental changes need to be made: electrification of the end-use sector, efficiency improvement, and decarbonization of the power supply. Similarly, many studies on decarbonization systems are based on these three perspectives [9]. Electrification development is often accompanied by further developmental measures [10]. Sheikh and Callaway [11] compared alternative zero-carbon strategies such as solar thermal, biogas, synthetic natural gas, and electrification, demonstrating that electrification is the most promising approach. The efficiency indicators are crucial factors in assessing the potential primary energy savings in any energy system modeling [12] and the potential for energy security realization and pollution reduction [13]. The modeling results presented in Ref. [14] suggest that a carbon tax combined with strong energy efficiency policies would generate synergies to achieve deep decarbonization. While energy efficiency improvements are driving the low-carbon transformation, another study [15] argues that it is necessary but not sufficient, and additional decarbonization of the power supply is required. The decarbonization of power supply usually adopts two methods: the transformation of the traditional thermal power [16] and increased penetration rate of RE [17].

RE plays a significant role in carbon emission reduction [18] and global energy conservation [19]. But at the same time, the higher penetration of renewable energy sources (RES) raises critical issues in the current centralized electric system. The intermittency of RE makes its integration with the power grid difficult [20]. From the above literature, it can be seen that the transformation and decarbonization of the energy system are closely related to the development of RE. At the same time, the existing resources also limit the high proportion of RE integration. Therefore, hybrid power systems can help solve the restrictions on the realization of the decarbonization system caused by resources and the relationship between supply and demand [21]. The volatility and randomness of a single RES can also be suppressed by the complementarity of different energy sources [22]. Different types of hybrid energy systems and multi-energy complementary strategies have been applied to energy optimization in many countries and regions [23].

The stochastic fluctuation of RES, the excess electricity, and the imbalance between the supply/demand also provide possibilities for storage systems [24]. Existing energy storage technologies include pumped hydro storage [25], compressed-air energy storage [26], batteries [27], electric vehicles, etc. Integrating storage system technologies into a hybrid power system provides a new path for the grid connection of RE power [28]. Energy storage systems are the most potent strategy to replace thermal power while achieving "peak-shaving" in grids [29]. To make better use of hybrid energy storage systems (ESS) for power system structure adjustment and peak regulation, various researchers have proposed their optimization structures for different systems. Zhao et al. [30] proposed a preliminary scheme of capacity allocation of a hybrid energy storage system for peak clipping in power systems. Sigrist et al. [31] evaluated two independent Spanish power systems and concluded that ESS is an economic alternative to dispatching the standby generating capacity of online units.

Hydropower is a reliable, versatile, and low-cost source of clean electricity generation and responsible water management. In 2020, the global installed hydropower capacity was 1170 GW and total hydropower generation amounted to 4370 TWh [32]. Many studies have shown that modern hydropower plants are helping to accelerate the clean energy transition, providing essential power, storage, flexibility, and climate mitigation services [33]. In fact, some studies have shown that replacing fossil-fueled electricity generation with hydropower has helped to reduce carbon dioxide emissions by 100 billion tonnes in the last 50 years alone [34]. This is roughly equivalent to the total annual carbon footprint of the United States for 20 years [35]. By analyzing the cost-optimal hydropower dispatch from a fully renewable energy system, Ebbe et al. [36] demonstrated that hydropower will play an important role in the energy transition and is important for decarbonization and improving the planning basis for future energy systems. Meanwhile, many hydropower plants can ramp their electricity generation up and down very rapidly when compared with other power plants such as nuclear, coal, and natural gas. This makes sustainable hydropower an attractive foundation for integrating greater amounts of wind and solar power. Tom Karier et al. [37] examined how hydropower can increase the capacity value and energy efficiency of renewable energy sources. Their findings showed that one of the contributions of hydropower to carbon reduction is to increase the capacity of new resources to meet peak loads. Gilton et al. [38] proposed that the use of hydropower channel locks can be used for energy storage and renewable energy integration. Therefore, hydropower is also a key asset in creating a safe, clean electricity system and achieving global net-zero goals, and the advantages of hydropower could make it a natural enabler of safe transitions in many countries.

As an important element of energy complementarity, hydropower regulation capacity can mitigate fluctuations of wind and photovoltaic power for meeting load demand [39]. This is due to its rapid response to load changes, robustness to weather fluctuations, and energy storage through the reservoir [40]. Hydropower stations are divided into large hydropower and small hydropower stations. Small hydropower is an indispensable and important part of the hydropower development process due to its small investment, short cycle time, and quick results [41]. Developed countries attach great importance to the development of small hydropower, which has become one of the pillars of electricity production in many EU countries [42]. However, the development of small hydropower has not always been smooth and there has been considerable controversy within various communities. The main focus of the controversy is the impact of small hydropower on the ecological environment. Small hydropower development can cause changes in the hydrology of natural water flow patterns [43], damage river ecosystems [44], have a potentially negative impact on the productivity of downstream plains [45], destroy species diversity, and hinder the reproduction and growth of specific fish species [46]. In particular, the impact is greater when the 'abandonment' of water is more severe.

Today, hydropower plays a key role in the transition to clean energy, not only because it produces large amounts of low-carbon electricity, but also because of its unparalleled ability to provide flexibility and storage. Many studies have utilized multi-energy complementary structures containing pumped hydro storage to reduce carbon emissions and mitigate peak-shaving tasks [47]. Yajun Tang et al. [48] verified that the combined operation of wind, photovoltaic and hydroelectric power stations increased the complementary benefits of the power system's output and ensures annual power generation with good daily power quality. Notton et al. [49] built a simulation tool for the operation of a hybrid PV/Wind plant coupled with hydro-pumping storage. Patwal and Narang [50] modeled the pumped storage hydrothermal system with wind energy sources. Xia et al. [51] used the complementary operating characteristics of pumped storage and other power types to propose a multi-time scale coordinated dispatch model, thus solving the power system imbalance caused by the grid connection of intermittent RES such as wind and PV. Xu et al. [50] designed and investigated a photovoltaics (PV)-wind-hydropower station with a pumped-storage installation (HSPSI) hybrid energy system. They found the optimal configuration with maximum power supply reliability and minimum investment cost. Some scholars have pointed out that scientifically managed small hydropower can help to achieve carbon neutrality goals [52]. Large-scale pumped storage power plants have a stronger energy storage capacity, but their construction limitations are also relatively large. Therefore, at a time when renewable energy power is developing rapidly and energy storage requirements are gradually increasing, developing small-scale pumped storage power plants to improve energy storage efficiency and enhance grid regulation with quantitative advantages is a realistic and good choice [53]. The aforementioned literatures show that the complementary operation of renewable energy and hydropower plants has the potential to increase the capacity of renewable energy in the grid. However, the challenge of optimizing the scale of renewable energy integrated into hydropower plants remains.

Sichuan is the first province in China to realize clean-energy-oriented energy production and structure (leading China's clean/low-carbon energy transformation) [5]. The power supply structure of Sichuan Province is mainly based on RE such as hydropower, wind power, photovoltaic power generation, etc. However, increasing hydropower installation has different disadvantages such as lack of power demand and limited external transmission channels. Therefore, it is very important to adjust the energy structure and improve energy efficiency. This includes the development of hydropower and clean energy. Government policies and current techniques limit the exploitation of natural gas in Sichuan [6]. In the short term, the prospect of developing gas power is not very broad. Moreover, it is urgent to take relevant measures to solve the major problems of surplus water and electricity in Sichuan. If the current structure of the energy system continues, CO2 emissions will rise dramatically [7]. Therefore, the objective of this study is to answer the following questions; (a) how can a low-carbon transition be realized in a region that is faced with the huge contradiction between the excess supply of hydropower and slow growth of energy demand, (b) how will the clean energy transition be presented in various terminal sectors, and (c) what impact will low-carbon transition have on the energy sector, technology, environment, and economy. These are the key issues that need to be studied in the paper with considering the process of realizing decarbonization goals.

Furthermore, the purpose of this research is to study the RE power generation structure and decarbonization path in the area with high hydropower penetration. Due to the advantages of hydropower in improving the absorption capacity of renewable energy, this paper chooses Sichuan electric power system, which is highly dependent on hydropower, as the research object. The other contributions of this paper to existing works of literature are summarized as follows:

(1) Hydropower is the key to achieving decarbonization goals in many countries. In the face of the many challenges that hinder the rapid deployment of hydropower, this paper proposes a hybrid energy system that uses hydropower as the main source of energy to achieve decarbonization and provides an effective solution to problems such as power abandonment that hinder the development of hydropower.
(2) Most of the decarbonization models for hydropower do not consider the impact of changes in hydropower capacity coefficients. Therefore, this paper is based on three scenarios with different hydropower output coefficients in wet, normal, and dry years to consider the future decarbonization pathways of the energy system under various hydropower generation capacities.
(3) Technical and economic studies were carried out using the EnergyPLAN model, taking full account of the main types of regional renewable energy and the constraints on development potential. A bottom-up decarbonization model was constructed by determining the energy supply mix and installed capacity based on future energy demand. And different scenarios were constructed based on different constraints, environmental benefits, and cost-effectiveness were compared while identifying various decarbonization paths.

Therefore the paper analyses the developmental status and potential of renewable energy in the medium-term based on existing technologies and policies in the case study. Then, an optimization model for reducing carbon emissions and solving the energy balance crisis in Sichuan Province by 2030 is proposed. This model will focus on 100% decarbonization, without considering the policy constraints.

The plan presented in this study will further analyze three aspects of the current electricity system for the case study. First, it will reflect the response of future energy systems to different hydropower scenarios. Then, the enhancement of RE penetration and reduced carbon emission are analyzed. Lastly, improvements in the utilization rate of hydropower and enhanced peak load regulation characteristics of the system. This paper presents an hourly analysis using the EnergyPLAN simulation program. To compensate for the lack of regulation capacity, pumped hydro storage is combined with hybrid RE technologies. Finally, the goal of reducing excess hydropower, reducing carbon emissions, replacing fossil energy, and improving energy efficiency will be achieved. Although Sichuan Province in China has been adopted as the research object, the versatility/applicability of the models in this study is universal (for areas with high hydropower potential). The remainder of this paper is divided into the following parts. Section 2 describes the tool and methodology adopted in the article. The analysis of results and discussion are presented in Section 3. Finally, our conclusions are noted in Section 4.

2. Methodology

To analyze the energy pathway of the case study and promote an appropriate electricity system structure by 2030, the methodology used in this study is divided into three parts. Firstly, the actual data of demand, supply, transport, and industry sections in 2017 are summarized to design a current reference scenario (REF). According to the results of the REF model, the quantitative characteristics of the energy system are obtained. Afterward, based on the current energy construction planning and the energy system developmental expectations of Sichuan Province, three models with different hydropower levels are constructed for 2030. The models mainly analyze the energy efficiency, development and utilization of space, environmental protection, and economic benefits of RE under future development policies.

Finally, the future optimized hybrid scenario for 2030 is designed based on estimations of future electricity demand, energy consumption, and energy structures by sectors and installed capacities of different resource and energy technologies. This model integrates energy such as hydro, solar, wind, biomass, and hydro-storage in the power system. Electricity and clean energy substitution technologies are adopted in the industrial and transportation sectors. It is worth noting that targeted energy optimization structures and alternative technology are adopted for the situation of power supply and demand under different hydropower levels. Also, the inputs and assumptions are defined in EnergyPLAN (the hourly energy system analysis tool). EnergyPLAN is used to make a quantitative analysis of the future scenarios of RE development under different policies and energy structures [54]. The system can be optimized and analyzed by continuously adjusting input and output based on the characteristics of the energy system under different levels of hydropower.

2.1. Current situation of the case study energy system

Sichuan is located in the southwestern part of China, with a total population of 83.02 million, ranking fourth among all provinces in China. This Province is rich in various energy resources including hydropower. In addition to the hydropower resources, conventional clean energy resources such as natural gas are in abundance in this area and used as one of the main petroliferous basins in China [55]. Based on investigative and exploratory data, the exploitable amount of hydroelectric resources in Sichuan Province is 148×10^6 kW, while feasibly, the exploitable amount is 145×10^6 kW [56]. On the contrary, coal and oil resources are relatively poor or non-existent in this area (accounting for 0.2% and 0.86% of the total reserves of China, respectively) [57]. Specifically, the RES quantity that is technically exploitable is shown in Table 1.

Sichuan ranks first in terms of clean energy installation and power generation in China. In 2017, the installed capacity of hydropower reached 77.14×10^6 kW. At present, its electricity transmission capacity reaches 30.6×10^6 kW. In 2017, Sichuan exported 138.9×10^9 kWh excess electricity, accounting for 43% of the total hydropower generation [58]. The mismatch between the rapid development of hydropower and the slow growth of power demand has led to the imbalance of power supply and demand [5], and in turn, caused a water/electricity surplus. Also, due to the insufficient power regulation capacity of hydropower [59], all Sichuan thermal power plants are forced to participate in peak load regulation. Meanwhile, the lack of self-regulation ability and the fluctuation of wind power and photovoltaic power generation will ultimately affect the power supply capacity of the system and increase the emission of pollutants, thereby reducing economic benefits and the reliability of power system operation [60].

2.2. Simulation tool

The decarbonization model building process places higher demands on the modelling and simulation of energy systems: (1) performing technical or economic simulations of different sectors, including electricity, personal/district/industrial heating, cooling, transport, storage, and various renewable generation and heating technologies, such as wind, hydro, solar and geothermal power generation in the power sector. (2) There is a need to carry out simulations on long time scales with a small-time resolution for the supply and demand balance of electricity and heat. This will help to achieve a quantitative analysis of the energy flows of electricity, heat, and hydrogen; (3) There is also a need to explore the scope and application effects of advanced technologies such as cross-sectoral synergistic support technologies and carbon capture technologies in future energy systems, and to provide possibilities for the application of advanced technologies for the efficient and clean energy transition.

To meet these requirements, the EnergyPLAN model was used in this study for simulation analysis. EnergyPLAN is an hourly deterministic input-output model designed for regional and national energy system analysis. The outputs of EnergyPLAN conclude primary energy source (PES), critical excess electricity production (CEEP), CO_2 emissions, etc. [61]. The EnergyPLAN model describes two aspects of the power system: energy generation and energy consumption. It can perform technical or economical simulations of different sectors including electricity, individual/district/industry heating, cooling, transport, storage, etc. [62]. This simulation program emphasizes the impact of different energy strategies or policies on the energy balance, environment, and economy of a country/region simultaneously. It also has a high degree of flexibility in application. On this basis, it has been used in predicting and evaluating the regional energy system to identify the optimal operation strategy [63]. Therefore, it is used for devising a future electricity system structure for Sichuan Province in this study.

Instead of traditional power generation, EnergyPLAN focuses on RE generation more. It accurately describes various RE power generations including hydropower, wind power, photovoltaic power, biomass power, etc. Meanwhile, it considers the fluctuation of RE and hourly distributions of different generations based on the historical electricity production data of the system [64]. Owing to precise simulation for RE power generation, the model is used to completely simulates the Sichuan electricity system which is based on hydropower primarily. Also, many advanced technologies applied in EnergyPLAN such as energy storage, heat pump, and electric vehicles can be integrated with the energy system. Therefore, when simulating the integration of high levels/quantities of

Table 1
The technically exploitable amount of Hydropower, Wind power, and PV.

	Category		This Study
Hydro Power Resource	River Hydro Power	Capacity (GW)	148
		Production (TWh/year)	676.4
Wind Power Resource	Onshore Wind Power	Capacity (GW)	48.5
		Production (TWh/year)	97
PV Resource	–	Capacity (GW)	105
		Production (TWh/year)	157.5

RES, EnergyPLAN is used as it takes into consideration the whole technical details of each technology needed in the study. EnergyPLAN has been used to model the energy systems in many countries/regions. Previous studies have used EnergyPLAN to analyze energy systems of different regions/nations such as Europe [65] and its internal countries [66–68], Nigeria [69], Brazil [70], and China [71]. The areas of research include decarbonizing electricity systems or heating systems [72], large-scale RES penetration or RE strategies [73], and multiple energy complementation of hybrid energy systems [74]. Previous studies for China using EnergyPLAN almost focused on provinces and cities in eastern China, which are dominated by thermal power.

Some of the limitations of the EnergyPLAN model include; (1) the lack of studies on energy production and site-specific decarbonization, such as zero-carbon power plants and zero-carbon substations. However, from an engineering point of view, most medium and long-term decarbonization models use renewable energy sources that produce little or no CO2, and the development of advanced technologies has led to a reduction in CO2 emissions during the energy production phase. In summary, the EnergyPLAN model can not be used to estimate the hourly CO2 emission. (2) the EnergyPLAN model is a deterministic input-output model and is not inherently capable of constraining the input parameters by means of relevant algorithms to take values within the required or requested range. However, it can be combined with other optimization models in the research process to find the optimal model within the theoretical range by continuously adjusting the input parameters and based on the output parameters such as CEEP and CO2 emissions.

2.3. The REF scenario

To provide an in-depth description of the current energy structure of the Sichuan power system and create a reference for future optimization scenarios, the reference (REF) scenario was developed. Taking 2017 as the reference year, the model is built comprehensively from the aspects of power demand, power supply, transportation, industrial sector energy consumption, etc. The actual data are mostly from the official statistics platforms at the national and provincial levels. From the Sichuan Electric Power Yearbook [58], data on social electricity demand, installed capacity, and generating capacity of various power generation methods were obtained.

Based on investigative and exploratory data, the exploitable amount of hydroelectric resources in Sichuan Province is 148×10^6 kW, while feasibly, the exploitable amount is 145×10^6 kW [56]. On the contrary, coal and oil resources are relatively poor or non-existent in this area (accounting for 0.2% and 0.86% of the total reserves of China, respectively) [57]. Specifically, the RES quantity that is technically exploitable is shown in Table 1.

By the end of 2017, the full-scale power generation capacity was reported as 345.72×10^9 kWh, and the total power generation of wind, hydropower, and photovoltaic power was 310.365×10^9 kWh, accounting for 89.77% of its total power generation. For traditional fossil energy power generation, the thermal power generation capacity was 35.373×10^9 kWh, accounting for the remaining 10.23% of the total power generation. Also, the installed capacity of thermal power only accounted for 17% of the whole province, which was 16.61×10^6 kW.

At the same time, fossil fuel consumption in thermal power, transportation, and industrial sectors was obtained from the China Energy Statistics Yearbook [75]. Due to the lack of proper definitions, uniform calibrations, and calculation methods in some data of China's energy statistics and international standards [76]. Therefore, it is necessary to use the corresponding adjustment rules to convert it into a terminal energy consumption that conforms to international general standards. The data adjustment rules of the transport department are shown in Table 2 and the data adjustment rules of the industrial department are shown in Table 3.

The REF scenario contains the distribution data of electricity demand and RE power generation. The hourly distribution data of electricity demand is obtained according to the monthly power demand curve in Sichuan province and the daily load curve of China based on the daily hourly load factor [77], as shown in Equation (1):

$$P_{\mathrm{d}-avs} = P_{m-avs} \times \frac{P_{d-av}}{P_m} \tag{1}$$

where $P_{\mathrm{d}-avs}$ and P_{m-avs} denote the average daily load and the average monthly load of Sichuan, $P_{\mathrm{d}-av}$ is the average daily load of China, P_m is the monthly load of China.

The distribution data of wind power and photovoltaic power is calculated from the output of wind/photovoltaic power generation every 15 min in Sichuan Province in 2017. The hydropower distribution data in the REF model can be obtained comprehensively by verifying the hydropower distribution data in the China 2020 model in EnergyPLAN and the daily hydropower generation data [78] in Sichuan Province. The specific hourly distribution data of electricity demand and supply are shown in Fig. 1.

The detailed results obtained from the modeling of the actual Sichuan power system using EnergyPLAN are present in Table 4. It shows that the EnergyPLAN simulation is closed to the actual energy data in 2017, the difference between the actual statistical data of power generation and the simulated value is insignificant, with a maximum error of about 0.14%. The difference between the actual electric quantity and the simulated value in the analysis model is about 1.62%.

Fuel consumption is another measure of the accuracy of the model. In the model establishment, the fuel consumption of the power sector, transportation sector, and industrial sector are mainly considered. The comparison between the actual total consumption of the system and the fuel consumption in the model is shown in Table 5. The fuel type with the largest difference between the actual data and the model simulation data is natural gas, with an error of 0.61%. This proves that the distribution data and supply data used in the model can well simulate the current energy system of Sichuan, and the assumptions used to develop the 2030 policy scenarios and 2030 optimization scenarios are based on the energy distribution in 2017.

2.4. The 2030 policy model

The 2030 scenarios reflect the relevant energy policies of the Chinese and Sichuan governments. Energy models of Sichuan Province in 2030 under three different hydroelectric treatment levels are established according to; Sichuan Province's 13th Five-Year Plan for Electric Power Development [79], Sichuan Province's medium and long-term development forecast for energy structure [80], and the future development potential of various energy sources in Sichuan Province.

2.4.1. Electricity sector

In Sichuan Province's 13th Five-Year Plan for Electric Power Development, the electricity demand of the whole Sichuan Province in 2020 was estimated. It was predicted that the electricity demand data in 2020 will be about 250×10^9 kWh [80]. The electricity demand data for the future is calculated with Equation (2):

Table 2
Principles for the adjustment of transport among various sectors.

Departments before adjustment	Petrol	Diesel	Departments after adjustment
agriculture	100%	–	Transport
industrial	95%	35%	Transport
Construction	95%	35%	Transport
Wholesale, Retail Trade and Hotel, Restaurants	95%	35%	Transport
Residential Consumption	100%	35%	Transport
others	95%	35%	Transport
Transport	–	–	Transport

Table 3
Principles for the adjustment of industry sheets among various sectors.

Departments before adjustment	petrol	diesel	Crude oil	kerosene	Other oil	Departments after adjustment
agriculture	–	100%			–	industrial
industrial	5%	65%	100%	100%	100%	industrial
Construction	5%	65%	100%	100%	100%	industrial

$$Y_n = Y_0 \times (1+\alpha)^n \tag{2}$$

where α refers to the annual growth rate, Y_0 is the electricity demand of the reference year, Y_n is the electricity demand in n years, n denotes the number of years between level years.

On this basis, according to the relevant research hypothesis, the growth rate of electricity consumption will decrease by 1% per decade from 2020 to 2050. The growth rate from 2021 to 2030 is set as 4%. Therefore, the total social power demand of Sichuan Province in 2030 is about 370×10^9 kWh.

For the power system supply, the input of hydropower, photovoltaic power generation, and wind power generation will be considered according to the type of power supply and the proposed power supply projects before 2030 in Sichuan Province. The 13th Five-Year Plan predicts the installed hydropower capacity of Sichuan Province is expected to reach 141.5×10^6 kW. However, due to the differences in the construction of hydropower stations in some basins, it is estimated that the actual installed capacity of hydropower stations in 2030 will be 13.035×10^6 kW [81]. In addition, hydropower distribution data in 2030 still needs to be forecasted. Hydropower generation varies with runoff. Based on the three representative years of wet years, normal years, and dry years, this study predicts the distribution of hydropower in 2030 and analyzes/predicts the power system of Sichuan Province in 2030 under three different conditions. The hourly trend curves of three different representative years are shown in Fig. 2.

Sichuan Province has formulated relevant plans for the construction of photovoltaic power generation and wind power generation. It is estimated that the installed capacity of wind power generation in Sichuan Province will reach 14×10^6 kW in 2030, and that of photovoltaic will reach 7.5×10^6 kW in the same year. Under the three policy scenarios, the installed capacity of photovoltaic and wind power remains unchanged. The distribution data of photovoltaic power generation and wind power generation in 2030 can be obtained according to the predicted output characteristics.

Due to the environmental constraints and developing trend of RE in the whole process, the development of the traditional coal-fired power plant is extremely slow. The province plans to install 18.74×10^6 kW of thermal power plants in 2030. The energy consumption of thermal power plants is based on the 2019 data, and it is assumed that there is no reduction in energy consumption (due to technological improvement) from 2019 to 2030. The installed capacities of Sichuan's 2030 policy model have been determined, and the specific planning values within the province are shown in Table 6 below.

2.4.2. Industry sector

According to a study on China's industrial sector energy demand from 2015 to 2050 [82], the high energy consumption by this sector, and the industrial energy demand will peak around 2025. Meanwhile, the industrial energy consumption structure is characterized by the decline of coal, the increase of natural gas and electric power, and the relative stability of oil products [83]. Therefore, it is assumed that the total energy consumption of the industrial sector in 2030 will be consistent with that of 2017, but the proportion of primary fossil energy will decrease, and the change rate of energy demand will be consistent with the change rate of all types of energy in China's industrial sector. Also, with the development of alternatives to electricity, it is assumed that the electric power demands of the industrial sector have been included in the social electricity demand.

2.4.3. Transport sector

The energy demand for the transportation sector was estimated based on the energy demand of three parts, namely freight transport, intercity passenger transport, and urban passenger transport [84]. Based on these, the energy demand in 2030 is calculated by using the increase in energy demand of the three modes of transportation in China as well as the change in energy structure presented in literature [85]. Considering the development of highways, railways, civil aviation, and waterway, the energy demand structure of the transportation sector in 2030 is forecasted and analyzed, as shown in the following equation:

$$\begin{aligned} D_{trans} &= D_F + D_P + D_C \\ D_{Fn} &= t_{Fn} \times (1+\alpha_F)^n \times E_F \\ D_{Pn} &= t_{Pn} \times (1+\alpha_P)^n \times E_P \end{aligned} \tag{3}$$

where D_{trans}, D_F, D_P, D_C refer to the total energy demand of transportation sector, the energy demand of freight transport, the energy demand of intercity passenger transport, and the energy demand of urban passenger transport respectively, t_{Fn}, t_{Pn} denote the freight or the passenger transport turnover of the year n, andα_F andα_P refer to the growth rate of the freight or the passenger transport turnover. E_F orE_P is the energy consumption per unit turnover of freight or the passenger.

The annual average growth rate of each transportation type is

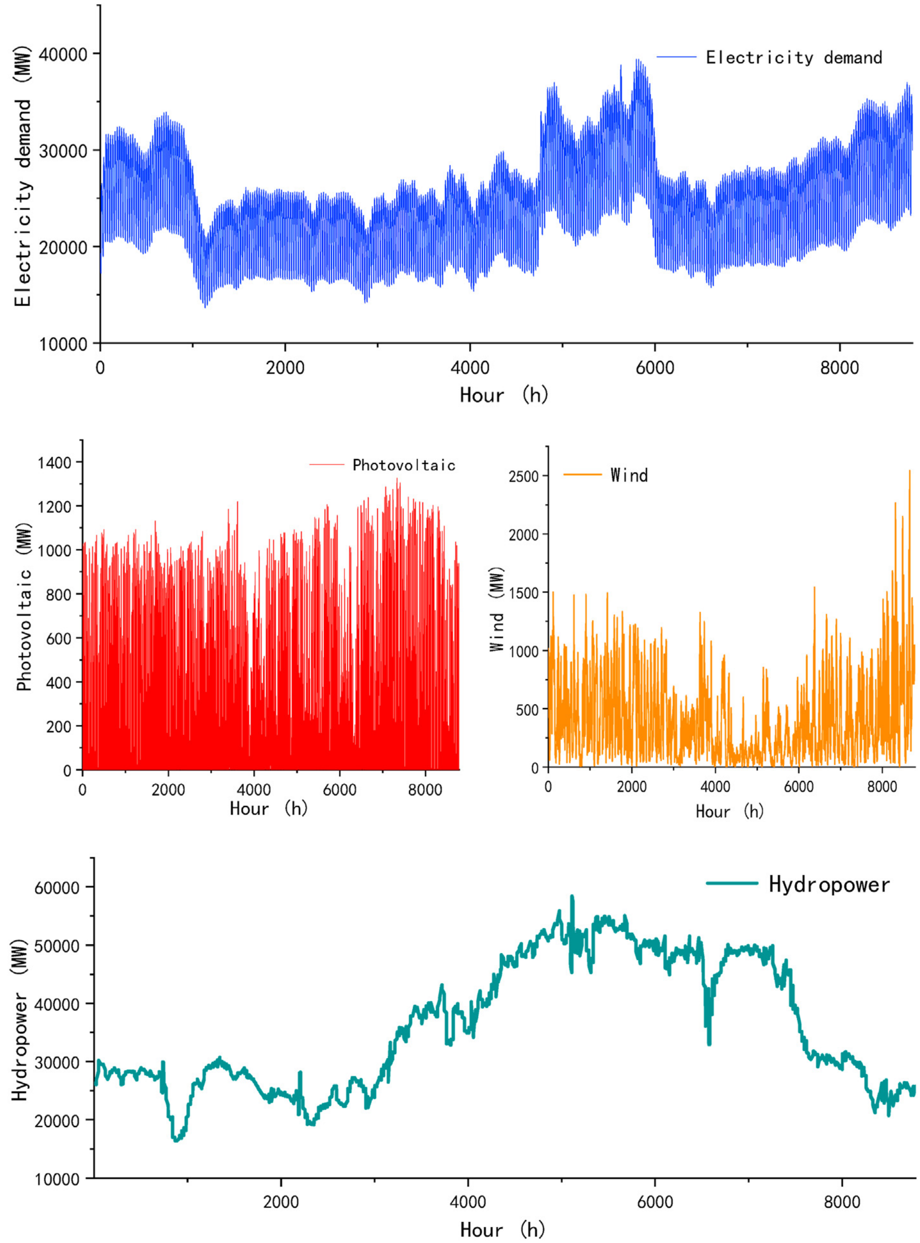

Fig. 1. Hourly distribution data of electricity demand, photovoltaic, wind power, and hydropower of REF model.

Table 4
Comparison of the actual data in 2017 and the simulation results of electricity generation.

Plant Type	Generation (TWh)		Difference (TWh)	Difference (%)
	Actual Data 2017	EnergyPLAN Model		
Electricity				
Hydro	316.4	316.51	−0.11	−0.03
Thermal	35.4	35.45	−0.05	−0.14
Wind	3.54	3.54	0	0
PV	1.65	1.65	0	0
Export	138.9	136.64	2.26	1.62

shown in Table 7. Combined with the structure of freight and passenger transport turnover in China and the proportion of fuel consumption in each traffic type, it is assumed that the energy consumption per unit turnover in Sichuan Province in 2030 will be the same as that in China.

The number of civilian cars carrying 1,000 passengers in the city remains consistent with the forecast value of China in 2030 [86], reaching 278 vehicles. According to Ref. [87], the urbanization rate of Sichuan in 2030 is 64%, the permanent resident population is 85.61 million, and the average number of trips per person per day is

Table 5
Comparison of the actual data in 2017 and the simulation results of total fuel consumption.

Fuel Type	Generation (TWh)		Difference (TWh)	Difference (%)
	Actual Data 2017	EnergyPLAN Model		
Coal	252.02	252.6	−0.58	−0.23
Oil	247.91	247.91	0	0
Natural gas	125.99	126.02	0.77	−0.61
Waste	3.89	3.89	0	0
Renewable energy	321.55	321.69	−0.14	−0.04
TOTAL	951.36	952.11	0.25	−0.02

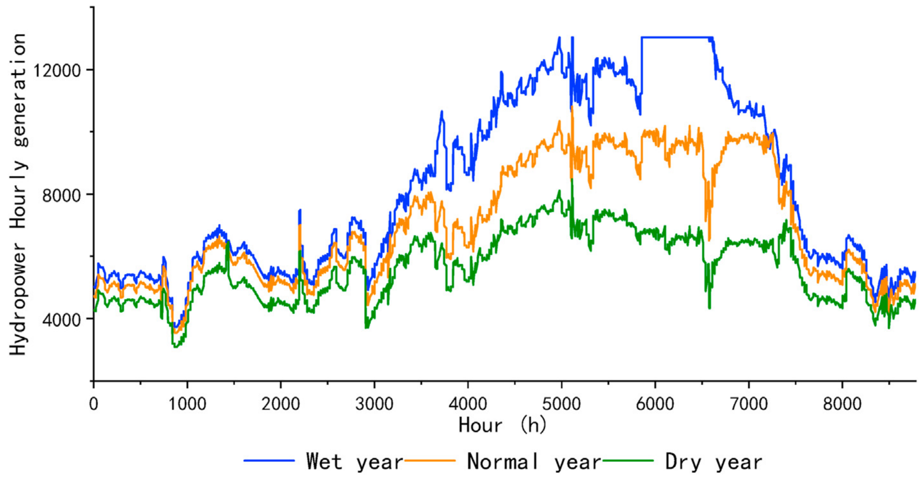

Fig. 2. Hourly distribution data of hydropower under different hydro levels of the 2030 model.

Table 6
Estimated installed power capacity in Sichuan by 2030.

Power Types	Estimated installed capacity in 203 (MW)		
Hydropower Level	Wet	Normal	Dry
Hydropower	130350	108094.6	84764.36
Thermal power	18740		
Including: Coal burning	12980		
Natural gas power	2700		
Residual gas pressure heat generation	2060		
Biomass, waste	1000		
Photovoltaic	7500		
Wind power	14000		

2.77. The distribution structure of urban passenger transport energy consumption in Sichuan is consistent with the domestic situation. The energy demand for urban passenger transport is shown as Equation (4):

$$D_{Cn} = k \times p \times u \times v \times E_c \tag{4}$$

where k is the number of civil vehicles, p is the population, u is the urbanization rate, v is the average number of trips per capita per day, E_C is the urban passenger transport energy consumption per trip.

2.5. The optimized 2030 model

In the construction of the 2030 optimization model, the technical premise is that the advanced energy technologies will not change before 2030, i.e., the technologies applied in the 2030 reference model already exist in 2017. However, from an economic point of view, the prices of various fuels and carbon dioxide, as well as the investment costs of hydroelectric, photovoltaic, and wind energy, have changed [80]. At the same time, in the feasibility studies of decarbonization of RE systems, only the capacity limits of a certain energy source or technology are considered, without considering the construction difficulties and development trends. In other words, it is assumed that all technologies and energy sources are feasible within the allowed range in Sichuan province.

2.5.1. The optimized scenario assumptions

The goal of 100% RE systems is to meet the energy demand of the remaining non-renewable parts of the energy system in all sectors only by electricity or other low-carbon clean alternatives [88], (such as hydrogen [89] from electrolysis and electric fuels and

Table 7
2030 growth rate of transportation types in Sichuan Province.

Type of Transport Sector	Annual growth rate of freight turnover	Annual growth rate of passenger turnover
Railway	5.8%	7.78%
Highway	7.04%	7.87%
Civil aviation	6%	8.667%
Waterway	5.1%	8%

biomass energy). This will certainly bring great challenges to the power industry and the development of advanced technology. However, given the abundance of hydropower resources in Sichuan, it is not impossible to achieve such a 100% power scenario in the Sichuan energy system in the future.

2.5.2. Electricity sector

The power supply of the electricity sector S in the optimization model is calculated by the following equation (5):

$$S = S_{H\max} + S_{PV\max} + S_{W\max} + S_{Bio} + S_{Storage} + S_{imp} \tag{5}$$

where $S_{H\max}$, $S_{PV\max}$, and $S_{W\max}$ refer to the power generation of hydropower, photovoltaic, and wind power with a maximum installed capacity of 2030. S_{Bio} is the amount of electricity generated by a biomass power plant within maximum potential installed capacity, $S_{Storage}$ denotes power generation of large energy storage systems, andS_{imp} denotes import electricity.

For the thermal power sector, biomass resources will be used primarily. Sichuan Province is rich in biomass energy. Every year, there are 31,485,300 tons of human and animal dung, 11,893,300 tons of firewood, 42,125,400 tons of straw, and about 1 billion cubic meters of biogas that can be developed and utilized, equivalent to 368.197 TWh in total [57]. The installed capacity of the thermal power department is assumed to be constant.

Meanwhile, decarbonization models are constructed for different level years:

(1) The import model (IMP) ensures that the capacity of the outward transmission channel is greater than the maximum amount of imported electricity, and considers the import of clean electricity from other neighboring provinces.
(2) The energy storage model (ESM) avoids importing electricity from other provinces by putting in maximum energy storage capacity, reducing the capacity of the outgoing corridor and increasing the installed capacity of thermal power plants, and putting in natural gas power stations and using carbon sequestration (CCS) technology to avoid carbon emissions for the part of the system that exceeds the biomass development potential.

2.5.3. Transport sector

The following assumptions are used for the modeling of the transportation sector considering electric energy substitution as well as hydrogen/biofuel substitution. Therefore, energy demand in the transport sector can be obtained by the following equation (5):

$$D_{Trans} = D_{Bio} + D_{H_2} + D_{Elec} \tag{6}$$

where D_{Trans} denotes the energy demand in the transport sector, D_{Bio} is the energy demand met by biofuels, D_{H_2} is the energy demand met by hydrogen, D_{Elec} is the energy demand met by electricity.

It's worth noting that biodiesel production efficiency of biodiesel is determined as 64.5% following literature [90]. However, for air transportation, biofuels are not the best choice because the carbon emissions produced in the process of producing biofuels are higher than the carbon emissions reduced by clean energy substitution [91]. Therefore, it is assumed that air and water transportation mainly consumes hydrogen.

Moreover, smart charging demand accounts for one-third of new electricity demand in the transport sector, with V2G (vehicle-to-grid) technology [92]. The largest share of EVs driving during peak hours and the largest share of EVs parking and connection to the grid is 40% and 80% respectively.

2.5.4. Industry sector

The industrial sector adopts clean energy alternative strategies, and the composition is shown in equation (7):

$$D_{Ind} = D_{Bio-I} + D_{H_2-I} + D_{Elec-I} \tag{7}$$

where D_{Ind} denotes the energy demand in the industry sector, D_{Bio-I} is the energy demand met by biofuels, D_{H_2-I} is the energy demand met by hydrogen, D_{Elec-I} is the energy demand met by electricity.

For the decarbonization system of 100% RE by 2030, the following assumptions are adopted:

(a) According to a previous study on the potential of industrial electrification in a large regional 100% RE system [93], 20% of the industrial sector is electrified.
(b) Considering the high demand for electric power by using hydrogen energy and the limitation of available capacity of endogenous material energy in Sichuan Province, it is assumed that 30% hydrogen is used and 50% biomass energy is used.

The final reference models constructed for the three-level years and the decarbonization model input parameters are shown in Table 8.

2.6. The economic costs

Economic analysis using EnergyPLAN focuses on the cost of investment and operating costs. The total investment of each production unit (I_{prod}) can be calculated by the following Equation (8):

$$I_{prod} = C_{prod} \times P_{Unit-prod} \tag{8}$$

where $P_{Unit-prod}$ is the per-unit price and C_{prod} is the total capacity of the production unit. The model then calculates the annual costs of each component divided into investment costs and fixed operation and maintenance costs. The total annual costs A_{total} and the annual investment costs $A_{Invest-prod}$ are calculated as Equation (9) and Equation (10):

$$A_{total} = A_{Invest-prod} + A_{O\&M-prod} + A_{v-prod} \tag{9}$$

$$A_{Invest-prod} = I_{prod} \times \frac{i}{\left[1-(1+i)^{-n}\right]} \tag{10}$$

where $A_{O\&M-prod}$ refers to fixed operation and maintenance costs, A_{v-prod} refers to variable costs, n is the lifetime given in years, and i is the interest.

The fuel cost, operation, and maintenance cost, life cycle cost, and other cost data for each year are based on the fourth edition cost database provided on the official website of EnergyPLAN [94] and are modified according to the actual situation in China and Sichuan Province [95,96].

3. Result and discussion

The results of the models developed in this research are discussed extensively in this section. The system response to the policy and clean energy structure of Sichuan Province's medium- and long-term energy model under different levels of hydropower generation are compared.

Table 8
The input parameters of the 2030 models.

Parameter	IMP	ESM	IMP	ESM	IMP	ESM
scenario	Wet year		Normal year		Dry year	
Demand(TWh)						
Electricity demand	361.5	603.59	603.59	603.59	603.59	603.59
Industry demand	302.41	302.41	302.41	302.41	302.41	302.41
Transport demand	296.8	296.8	296.8	296.8	296.8	296.8
Supply(GW)						
River Hydro	141.5	141.5	117.34	117.34	92.015	92.015
Wind power	48.5	48.5	48.5	48.5	48.5	48.5
PV	105	105	105	105	105	105
Thermal plant(biomass)	16.68	0	16.68	0	15	72
Other indicators(GW)						
Transmission line capacity	64.6	54.5	64.6	27.5	64.6	0
Charge capacity	128.3	138.4	91.5	128.6	59.3	123
Discharge capacity	98.7	84.3	56.1	69	40	135.7
Hydro storage(GWh)	40581	61705	10915	98615	395	19040

3.1. Analysis of supply structure of 2030

Based on the EnergyPLAN model, the policy reference model under different hydroelectric output, various types of power generation in 2030 under three scenarios are obtained. The output values of the policy model under the three scenarios in EnergyPLAN were compared with the data in the 2017 reference model, and the specific output values and proportion comparisons were shown in Table 9 and Fig. 3 respectively.

In the wet year, the hydropower generation is large from July to October, the output is close to the installed capacity of the system, and the annual hydropower utilization hours can reach 5,593 h. Compared with the power generation structure in the 2017 reference year, it can be found that from 2017 to 2030, with the increase of hydropower installed capacity from 77.14 million kW to 130.35 million kW, the power generation has nearly doubled, and the proportion of power generation has increased from 89% to 93%. The power generation proportion of thermal power plants will decrease yearly. From 2017 to 2030, the power generation capacity of thermal power plants decreased and the overall proportion decreased by 6%. With the closure of small coal power plants and the energy structure transformation of large thermal power plants, traditional thermal power plants are replaced by new energy power plants. The proportion of photovoltaic power generation and wind power generation has increased significantly. By 2030, photovoltaic power generation will account for 2% of the total power generation, and wind power will account for 4% of the total power generation. With the increase in the proportion of power generation, new energy power generation will make up for the deficiency existing in thermal power plants.

The power structure in normal years is similar to that in wet years, and the difference in power generation between wet and dry seasons is smaller than that in wet years. The maximum hourly output is 107094.6 MW, and the annual hydropower utilization hours are 4730 h. In this scenario, the share of hydropower is nearly equal to 92%, and it is still in the dominant position. Thermal power generation accounted for 1% of the total power generation. PV and wind power generation are the same as in wet years, but the proportion of electricity generation is higher because the proportion of hydropower is lower.

The power structure in a dry year is different from that in a wet year and a normal year, and the hydroelectric power supply is relatively insufficient. The annual utilization hours are 3785 h, and the maximum hourly output is only 84764.36 MW. Due to the lack of water and electricity in the system, a large amount of thermal power input is needed. The proportion of thermal power has decreased by 8%. Due to the small difference between the abundant and low power generation of hydropower, the advantage of hydropower output is not obvious, and the installed capacity of new energy is higher than that of 2017, the proportion of photovoltaic power generation and wind power generation will increase to 2% and 6% respectively in the dry year of 2030.

Table 9
Sichuan power generation comparison table 2030.

Power source	Wet year(TWh)	Normal year(TWh)	Dry year(TWh)
Hydropower	729.01	616.59	493.43
Thermal plant	8.87	9.62	11.8
PV	11.25	11.25	11.25
Wind power	33.61	33.61	33.61
Fixed export electricity	366.76	299.26	186.3
Export electricity	226.84	129.51	32.47
CEEP	45.97	1.81	0

3.2. Power system supply and demand in different scenarios in 2030

3.2.1. A wet year - scenario supply and demand analysis

The hourly supply and demand structure and balance curve of the model output in the scenario policy model in a wet year is shown in Fig. 4, Fig. 5, and Fig. 6. According to Fig. 4 (which shows the scenario model of the 2030 wet year), a large amount of electricity still needs to be transported to other provinces through the external transmission channels in this period due to the high hydropower output in the wet season and the fixed agreement of external transmission. However, there is a significant difference in the hydropower output in the wet and dry seasons, and the hydropower output in the dry season is insufficient. At this time, the provincial power generation is mainly used to meet the provincial electricity demand and the agreement delivery demand, and the export power is very low. Since hydropower occupies 93% of the total capacity, system capacity from March to October is mainly composed of water and electricity and small amounts of new energy power, and from November to February (Fig. 5).

This is caused by the insufficient hydropower generation capacity, though photovoltaic power and wind power generating capacity are complementary to hydropower generation. Due to the small installed capacity, efficiency is low, therefore, there is a need for thermal power input. Fig. 6 summarizes the supply and demand structure under the scenario of the wet year. The lack of regulating capacity of hydropower and the large difference in output during a

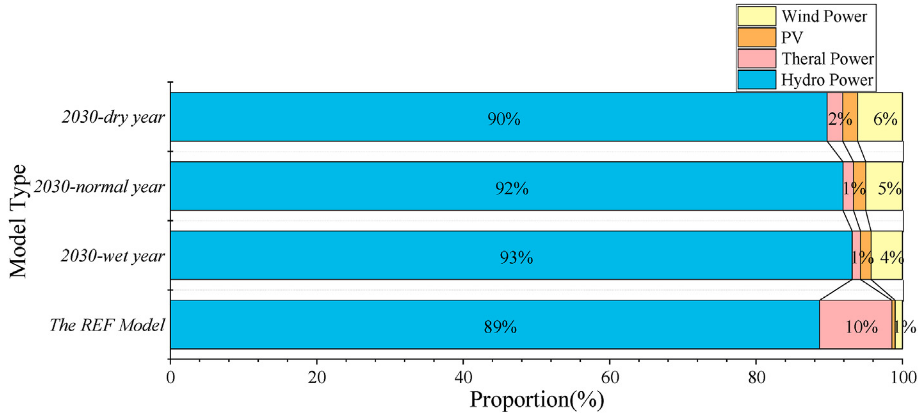

Fig. 3. Proportion comparison of various types of electricity generation at different levels in Sichuan in 2030.

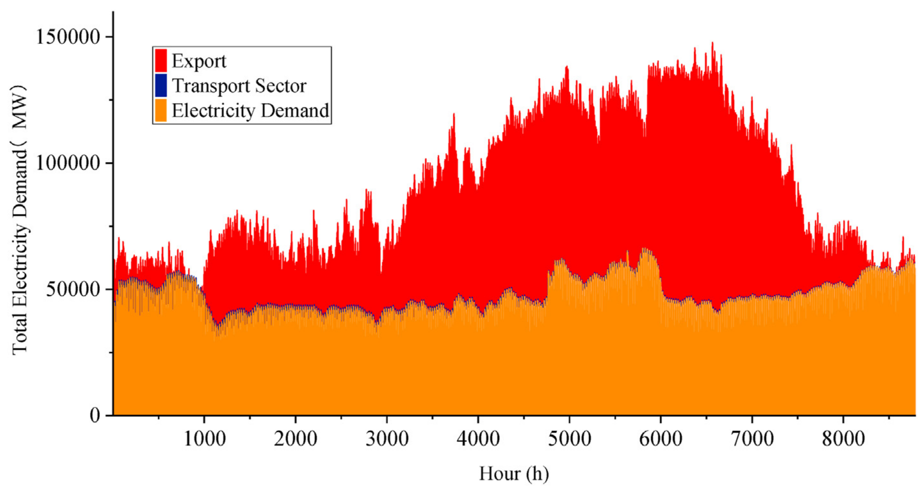

Fig. 4. The hourly demand structure of the wet year.

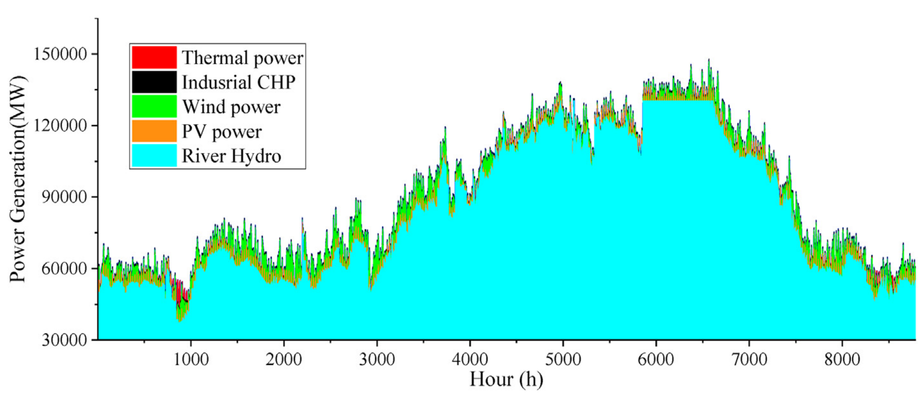

Fig. 5. The hourly supply structure of the wet year.

wet year led to a serious imbalance between the supply and demand of the system.

3.2.2. A normal year-scenario supply and demand analysis

The hourly supply and demand structure and balance curve of the model output in the normal year scenario policy model is shown in Fig. 7, Fig. 8, Fig. 9. According to Fig. 7, compared with the model in a wet year, the export power of the system is reduced. In the dry season, almost all the generated power is used to meet the province's electricity demand, and the export power during the wet season is significantly reduced. According to Fig. 8, from March to October, the power generation of the system was mainly provided by hydropower and a small amount of new energy generation, and the main peak appeared in July to September. However, from November to February, due to the lack of hydropower generation, photovoltaic power generation and wind power generation will

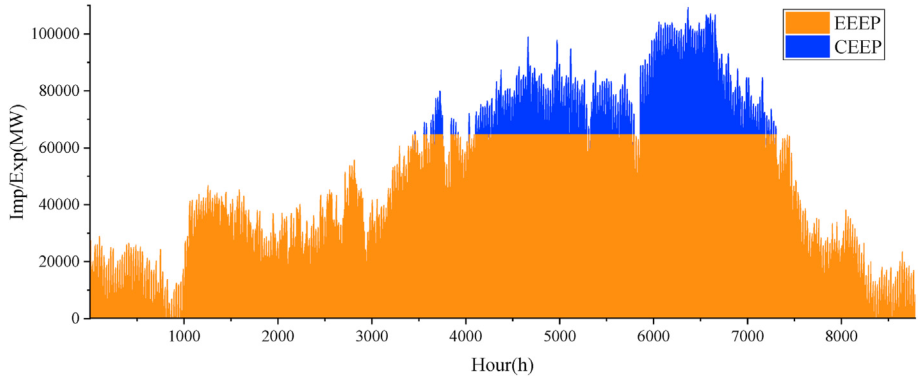

Fig. 6. The hourly supply and demand balance curve of the wet year.

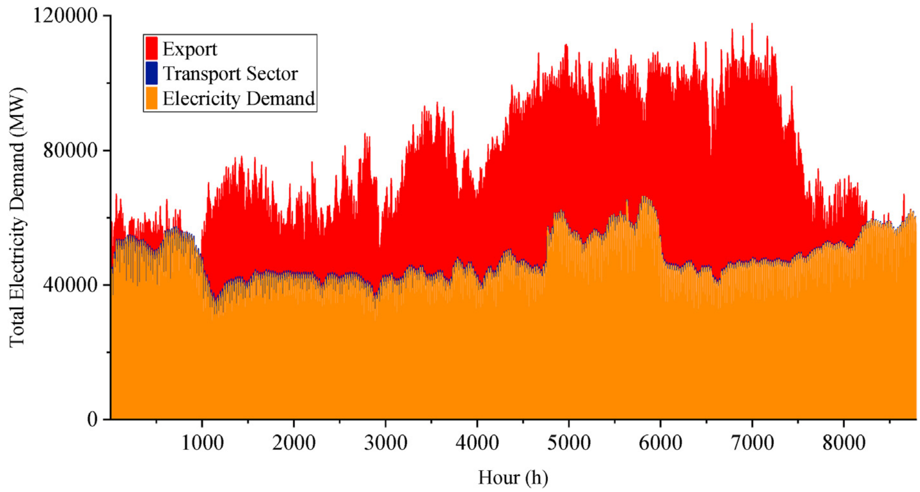

Fig. 7. The hourly demand structure of the normal year.

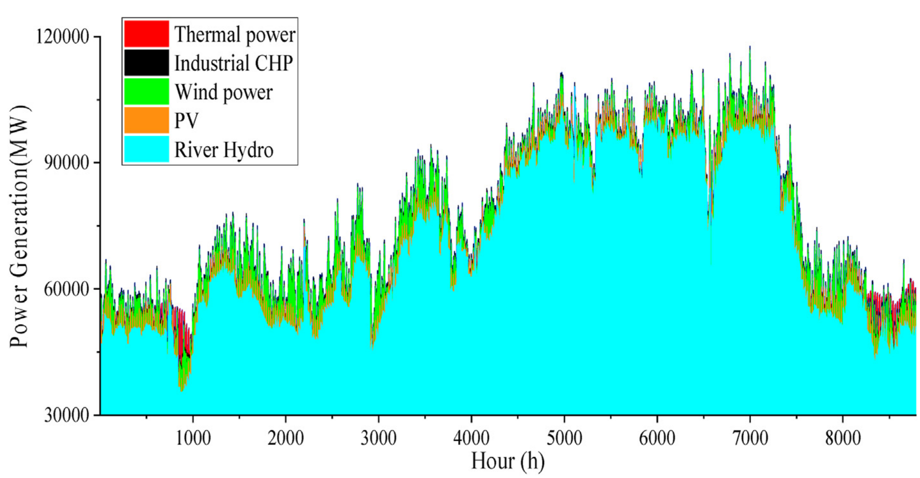

Fig. 8. The hourly supply of the normal year.

increase in power generation and complement hydropower. Also, due to the small installed capacity and low power generation efficiency, power shortages cannot be met by hydropower. Therefore, thermal power integration is still needed. According to Fig. 9, there is a trough of hydropower generation in winter, so more imported power input is needed in comparison to the scenario of a wet year. Through the analysis of the balance curve of supply and demand, it can be found that under the normal year scenario, the power system still has a certain amount of power surplus.

3.2.3. A dry year - scenario supply and demand analysis

The hourly supply and demand structure and balance curve of

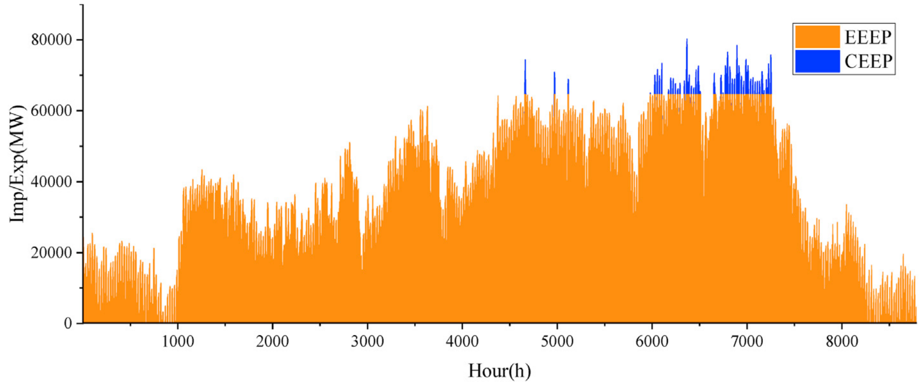

Fig. 9. The hourly supply and demand balance curve of the normal year.

the model output in the dry-year scenario policy model is shown in Fig. 10, Fig. 11, and Fig. 12. According to Fig. 11, the province's electricity demand in dry years accounts for most of the total demand, and export power decreases significantly, especially for the two peak seasons of electricity consumption in winter, export power is zero in some hours. According to Fig. 12, there is a power shortage in winter and spring, so in this scenario, thermal power plays the role of peak regulation and meeting the power demand throughout the year, and the input of thermal power increases significantly. According to Fig. 13, there is no excess electricity generated in the scenario of a dry year, and the export power can only maintain fixed export electricity.

3.3. Benefit analysis of the 2030 policy model

3.3.1. Environmental benefits

The carbon emissions of the simulation system in 2030 under the three scenarios were analyzed respectively and compared with the carbon emissions in 2017. The specific emissions are shown in Fig. 13. It can be seen from the figure that, based on the government's energy conservation and emission reduction policies in the power system, industrial sector, and transportation sectors before 2030, as well as the electricity substitution policies, the carbon emissions under the three scenarios in 2030 are reduced by 11.19%, 12.05%, and 12.3% respectively compared with the 2017 reference year model. This is due to the significant reduction in thermal power input under the three scenarios, the increase in energy utilization, and the decrease in the proportion of coal and oil consumption.

It is proved that although the energy consumption of the transportation and industrial sectors is higher than that of 2017, the relevant policies adopted by the government and the adjustment of the fuel structure make the energy system structure develop towards the direction of low carbon. However, due to the limitations of technological upgrading and energy structure improvement, there is still a large amount of carbon dioxide produced. Therefore, under the premise of reaching the carbon peak in 2030 and achieving carbon neutrality in 2060, the carbon emissions of Sichuan's energy system and power system at different levels should be lower than that of 2030. The decarbonization of the industrial sector, transportation sector, and power sector should be realized before 2060.

3.3.2. Economic benefit

Using the policy model under different scenarios in 2030, the estimated total cost in Sichuan Province in 2030 is calculated and compared with the total cost in 2017 (as shown in Fig. 14). The overall energy consumption in the industrial and transportation sectors increases with the full-scale industrialization by 2030, and the increase in the unit cost of fuel leads to an increase in the total fuel cost of the system compared to 2017. Due to the increase in the installed capacity of all types of power sources, the total investment

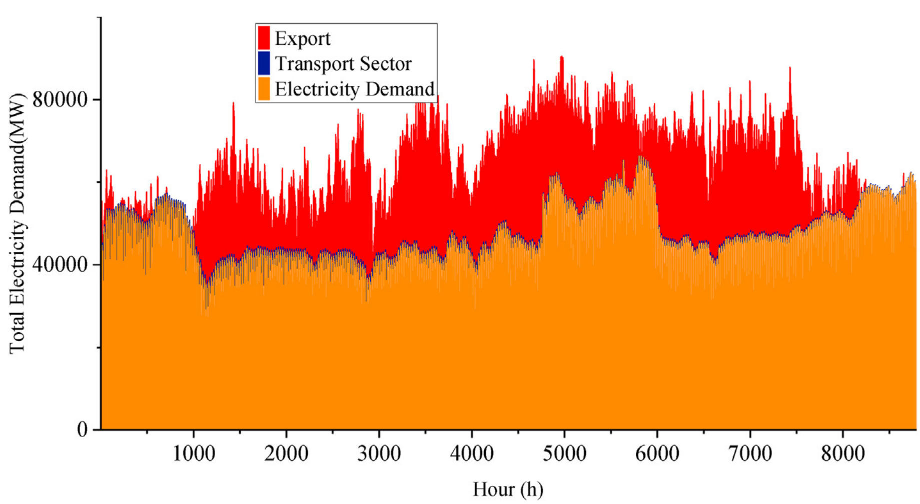

Fig. 10. The hourly demand structure of the dry year.

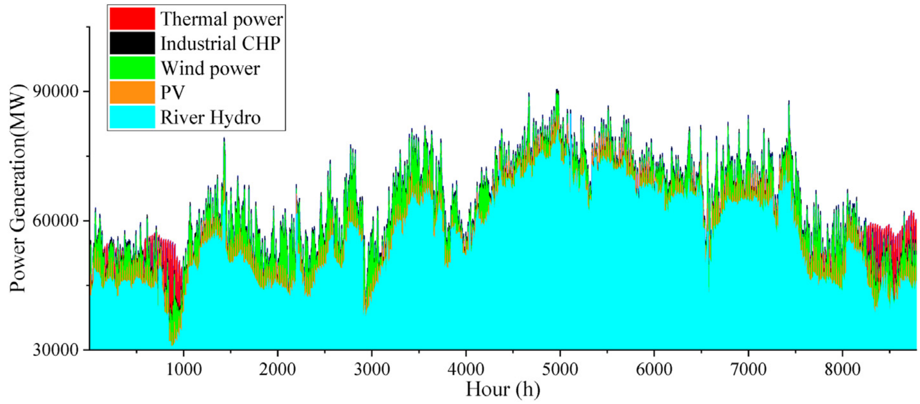

Fig. 11. The hourly supply structure of the dry year.

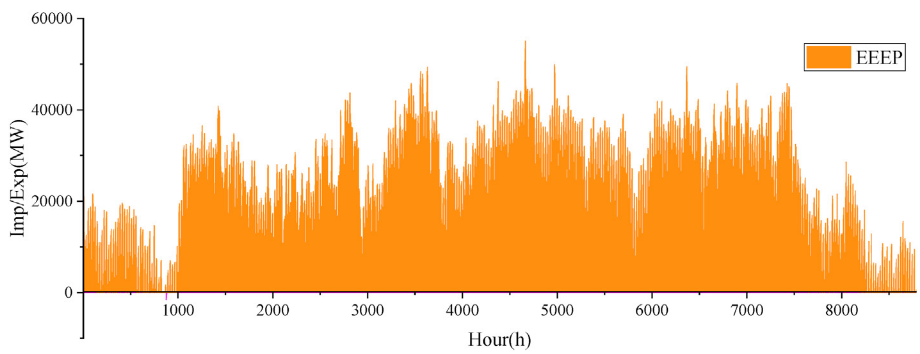

Fig. 12. The hourly supply and demand balance curve of the dry year.

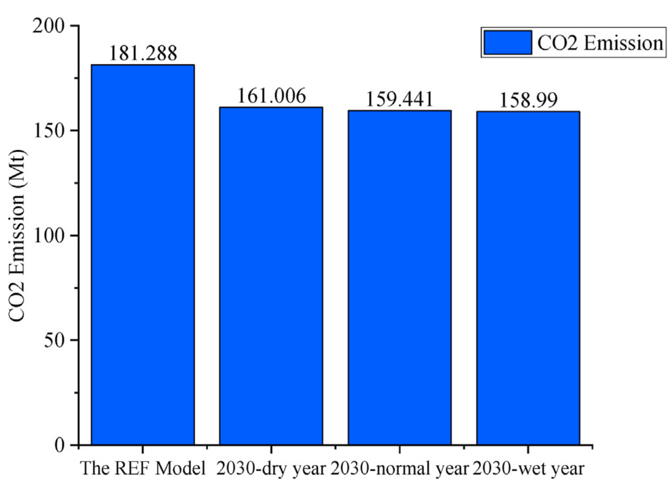

Fig. 13. The carbon emissions of the simulation system in 2030.

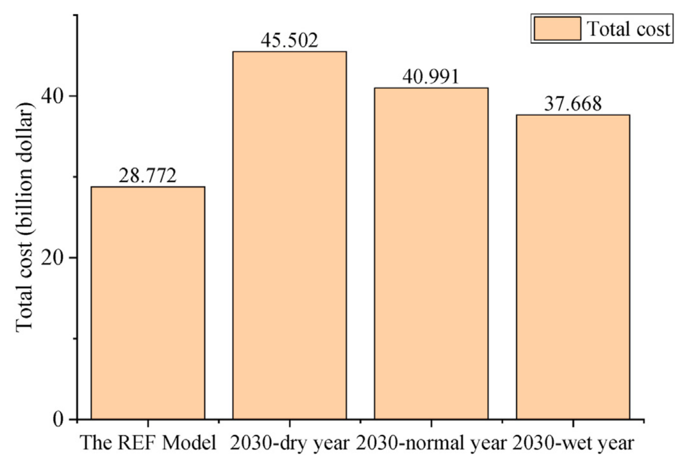

Fig. 14. The estimated total cost in Sichuan Province in 2030.

and operating costs increase year by year, although the unit investment costs are lower than in 2017. Meanwhile, the hydropower feed-in tariff is reduced from 48 $/MWh in 2017 to 46 $/MWh. As a result, the costs under the three scenarios increase by 58.14%, 42.47%, and 30.92%, respectively, when compared with the total system costs in the 2017 REF model. The increase in total system cost fully reflects the demand for electricity, fuel, and other energy sources for the socio-economic development of Sichuan Province until 2030. It also increased energy demand, the unreasonable energy structure, and the improvement of energy-saving technologies, as well as the insufficient development of alternative fuel technologies. This will bring a heavy burden of more economic benefits to society. In the three scenarios in 2030, the total cost will decrease as the amount of conventional thermal power input decreases and the degree of clean substitution of fossil fuels increases.

3.4. The optimized 2030 decarbonization scenarios results

The output parameters of the 2017 reference year model, the 2030 policy model for different level years, and the 2030 optimized model for different level years are compared to analyze the feasibility of optimization. The constructed optimization model is compared with the policy model from three perspectives of electricity supply and demand as well as environmental and economic benefits.

3.4.1. Power supply and demand structure analysis

For the 100% RE optimization model in 2030, all electricity supply will come from RE. The supply and demand structure differs due to the different installed capacities of supply measurement units for different decarbonization models at different level years.

(1) Model for 2030 with the wet year

The supply and demand of the three models under the year of abundant water in 2030 are shown in Fig. 15. The reference model has a serious imbalance between supply and demand in each sector, with unconsumed CEEP generation of up to 45.97 TWh while keeping the outgoing capacity unchanged. at this time. And hydropower generation is abundant, with outgoing power reaching 366.76 TWh. After structural optimization in each sector, the system generates a large amount of power demand. Assuming that all imported power is clean power from neighboring provinces such as Tibet and Yunnan, avoiding the import pattern of new biomass plants would require 5.76 TWh of power imports. However, since the internal line transmission channel in EnergyPLAN must be used for both import and export of electricity, and the energy storage system is only used to reduce unconsumed CEEP, 268.79 TWh would need to be delivered outward at this point, i.e., Sichuan Province would still act as the grid feeder.

To eliminate the excess power generated by the system, a pumped storage system is put in place to adjust the output so that the decarbonization model eventually has stability and always maintains a balance between supply and demand. The energy storage system represents an extreme case when the model mainly ensures that all the electricity demand in the model is met by the province. In other words, the line transmission capacity is minimized, forcing the system to generate CEEP. a large number of energy storage systems are put in place so that the imported power is 0. With 0 imported power, it is possible to export 245.83 TWh of power outside the province, in addition to meeting the provincial power demand.

(2) Model for 2030 with a normal year

Fig. 16 shows the supply and demand for the three models for the 2030 flatwater year scenario. The reference model still has a supply-demand imbalance, generating 1.81 TWh of unconsumed CEEP and 299.26 TWh of EEEP while keeping the transmission capacity constant. For the optimized decarbonization model, the system is forced to import more power from outside the province to meet the power demand of all sectors in the province, at which point the import model would need to import 26.21 TWh of power to meet 4.8% of the electricity demand. Similarly, due to the definition related to line transmission capacity within the EnergyPLAN model, the model can only maintain a balance between supply and demand when a pumped storage system is put in place, at which point the import model would need to transmit 194.71 TWh electricity to be transmitted to other provinces as export electricity. In the energy storage model, the line transmission capacity is significantly reduced and a large amount of energy storage system is put in to store CEEP, which makes the imported power zero at this time.

(3) Model for 2030 with the dry year

Fig. 17 shows the supply and demand scenarios for the four models under the 2030 dry year. In the reference model, the power generation decreases significantly. At this point the system no longer produces CEEP and the export electricity is 180.55 TWh of electricity. After the clean energy substitution, the import model has achieved the maximum capacity application of biomass at this point, with imports of 60.18 TWh, or 11% of the total electricity demand. At this point, the model transmits 130.15 TWh of electricity outward, which cannot be stored and does not meet the provincial electricity demand. The storage model reduces the line transmission capacity to 0 and puts in pumped hydro storage plants, while significantly increasing the installed capacity of thermal power plants. In this model, the supply and demand of the system are perfectly balanced, with no electricity imports and no electricity exports.

3.4.2. Carbon emission analysis

The primary energy consumption for different scenarios in 2050 for different models is shown in Table 10. The reliance on biomass as well as other fossil energy sources gradually increases as the hydroelectric power generation capacity decreases in the years of abundant water, flat water, and dry water. In EnergyPLAN, biomass, as a clean energy source, does not produce CO2 and therefore has good environmental benefits in replacing conventional coal and gas-fired power plants in the model.

By the end of 2030, the goal to achieve zero CO2 emissions in Sichuan province through energy substitution related technologies,

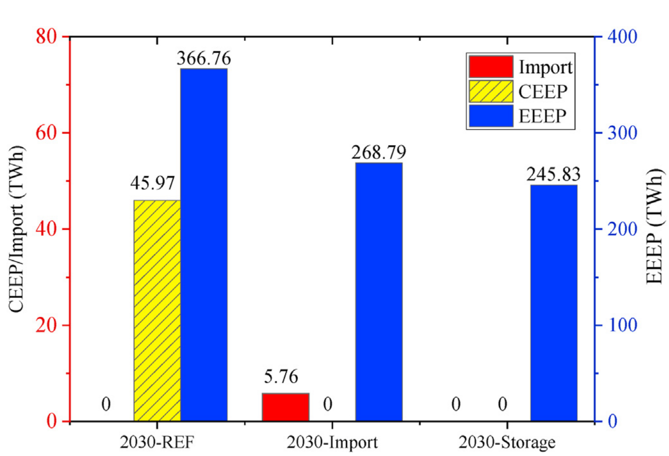

Fig. 15. The supply and demand balance in a wet year in 2030.

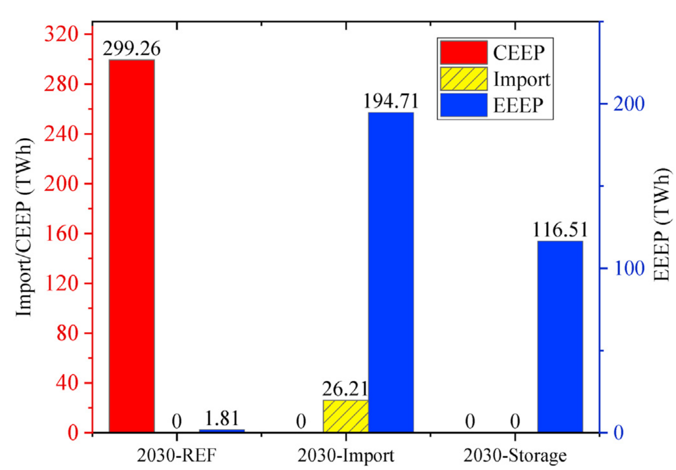

Fig. 16. The supply and demand balance in a normal year in 2030.

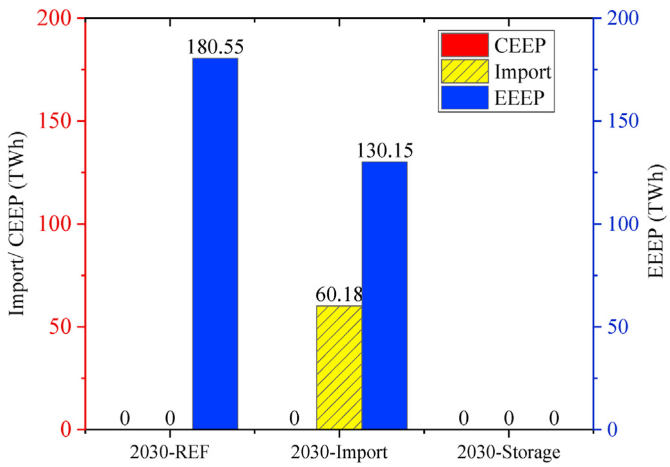

Fig. 17. The supply and demand balance in a dry year in 2030.

for different years of hydropower generation levels, although the power supply structure varies, the primary energy supply consists mainly of dominant clean and RE generation, all eventually achieving zero carbon emissions from the system. 2030 policy reference model for Sichuan energy system peaks in carbon emissions. In the optimization model, all three different levels of hydropower generation achieve significant reductions in system carbon emissions, eventually to zero, due to energy efficiency improvements and more aggressive energy substitution options. the reduction in carbon emissions demonstrates the feasibility of decarbonizing 100% of the RE system in Sichuan province by 2030, eventually achieving zero carbon emissions in the different scenarios of the decarbonization model.

3.4.3. Model costing

Fig. 18 shows the total system costs for the three models for three different scenarios in 2030. In contrast to the reference model, the other two models are 100% renewable energy systems with zero carbon emissions. The investment and O&M costs increase in the optimization model due to the significant increase in the installed capacity of renewable energy sources and the continuous investment in clean energy alternative technologies in the industrial and transportation sectors. However, the variable costs decrease substantially due to the cost superiority of clean energy alternatives. For the import model, the cost difference between the import and reference models is small.

In contrast, for the energy storage model, the cost increases substantially compared to the other models due to the large increase in installed capacity of the new energy storage system. By comparing the costs of different decarbonization models in each case, it can be seen that the import model has the lowest costs and the best economics.

Although there is an increase in the total cost of the optimization model compared to the policy model. However, this is mainly for the investment and operation costs arising from the large number of energy storage systems put in place, while this cost data is based on the data in the policy model. In the future, the continuous development of energy storage system technology will reduce the investment and operation cost of energy storage, thus reducing the total cost of the system.

3.5. Discussion

Through the comparative analysis of the supply and demand structure of different decarbonization models under the three hydropower levels, and the comparative analysis of environmental benefits, it can be found that there is a large gap in the energy structure in the years of different levels. Among the decarbonization models, the installed power supply capacity, delivery channel capacity, and energy storage system capacity of the biomass and the energy storage model all have huge differences due to changes in the system's supply and demand structure. Again, the comparative analysis of economic benefits in the previous section shows that the imported model has the lowest costs. The imported model can therefore be used to clean up and decarbonize the energy system through the complementary transmission of electricity from Sichuan province to other provinces, provided that the neighboring provinces have good outward transmission capacity.

The energy storage model is an extreme hypothesis under the assumption that Sichuan Province is an island-like operation mode that only exports but not imports. Without considering the investment cost at this time, the energy storage model has research significance and reference value in real applications, and because the province's electricity demand is all met by the province's power generation, the reliability is higher. Considering a situation where the transmission channel can only import electricity, all the excess electricity will be stored using the pumped-storage technologies such as to meet the power shortage at other times. Thereby reducing the dependence on external electricity saving, and ultimately improving the system's independence and reliability.

As hydropower is difficult to predict accurately, the universality of the decarbonization model should be considered when determining the energy optimization structure under different scenarios. The IMP model is more uniform and flexible. If the energy storage model or the biomass model is adopted, the energy structure needs to be adjusted according to the maximum value of each capacity of the model under the three scenarios, which has low

Table 10
Primary energy consumption in 2050 for different models under different scenarios.

Unit: TWh	Biomass energy consumption	Total primary fuel consumption	Natural gas consumption
Wet year			
The REF Model	0.28	592.11	130.02
Import Model	245	245	0
Storage Model	218	218	0
Normal year			
The REF Model	0.62	594.00	130.60
Import Model	292.66	292.66	0
Storage Model	218.23	218.23	0
Dry year			
The REF Model	1.80	600.57	132.62
Import Model	368.04	368.04	0
Storage Model	284.23	284.23	0

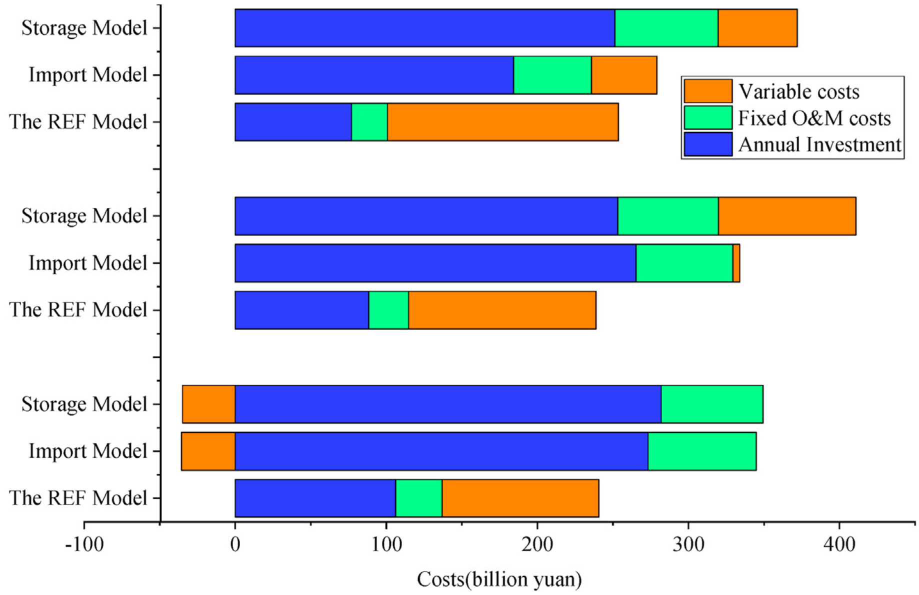

Fig. 18. Comparison of total system costs in different scenarios of 2030.

flexibility and will cause an excess installed capacity to varying degrees. Also, through the comparative analysis of economic benefits, it can be found that the import model has a lower cost. Therefore, when neighboring provinces have good delivery capabilities, the IMP model can ultimately achieve a clean energy system and decarbonization through the complementary transmission of electric energy.

According to the current trend of energy structure, by 2030, the case study will have a further imbalance between energy supply and demand. Under the current government's energy development policy, the energy supply revolution will continue to advance, supply capacity and quality will continue to improve, and the capacity structure in key areas such as industry will continue to be adjusted and optimized. Although the environmental and economic benefits will increase, the impact will be small and there will still be significant CO2 emissions. The decarbonization model constructed in this study utilizes clean energy substitution and advanced innovative technologies to effectively address the imbalance between energy supply and demand in Sichuan Province while achieving zero carbon emissions from the energy system. The decarbonization model constructed in this study makes integrated use of electrical energy, hydrogen, and biomass energy. It can be found that in the future system, electricity alone may not be able to bridge the gap between the supply and demand of complex energy sources. The use of multiple clean energy sources, which complement each other in time and space and make full use of the advantages of other energy sources to bridge the electricity supply gap. This can effectively solve the current energy problems in the case study. This is also of reference value to other regions and countries with serious carbon emissions and imbalances in electricity supply and demand.

Building a clean, low-carbon, safe and efficient energy system is in the direction of future energy development. This will vigorously enhance the green and low-carbon level of energy and accelerate the development of wind and solar energy. This will also develop hydropower according to local conditions and give full play to its advantages. At the same time, the construction of regulating power sources such as pumped storage and new types of energy storage should be accelerated to enhance the flexible regulating capacity of the power system. This can significantly improve the level of new energy consumption. The change of non-fossil energy alternatives in key industries and fields while accelerating the development of new energy vehicles and other green ways of using energy must be continually promoted. Also, the construction of production metering, regulation capacity and intelligence, building smart energy systems, accelerating the demonstration and application of hydrogen energy, and energy storage technologies must be promoted in this region.

The results of the study show that if carbon neutrality is achieved by 2030, the installed capacity of the electricity supply will increase significantly in a short period of time. At the same time, the power, industry, and transport sectors will need to undergo an accelerated transformation, which will be limited by time and technological developments. The high volume of electricity exports and imports also places high demands on transmission lines. At the same time, the cost of advanced technologies such as energy storage remains high and large-scale investments in energy storage systems will lead to higher costs. A long-term decarbonization model can therefore be built on the basis of medium-term studies. Make full use of the advantages of renewable energy sources such as hydropower in Sichuan. Actively apply advanced technologies such as electric vehicles and carbon capture, and accelerate the development of key core technologies, which can significantly reduce investment costs. Ultimately, the problem of hydropower abandonment in areas with high hydropower penetration will be solved, and the goal of carbon neutrality will be fully realized while achieving the best environmental and economic benefits.

4. Conclusion

This paper analyses and verifies the current problems of RE in Sichuan Province based on the EnergyPLAN model, and proposes hypotheses and reflections on the future structure and development prospects of RE in Sichuan Province. The internal theoretical and technical components of the EnergyPLAN model were used to simulate the energy system in Sichuan Province under existing technologies and policies. Three 2030 policy models were developed by building a reference model for 2017 and a policy model for 2030, under the policy premise of achieving peak carbon in 2030, with three hydropower output scenarios: abundant water year, flat water year, and dry water year. The data sources were mainly derived from projections in various studies and government policy prescriptions. The policy models are then analyzed in terms of the power mix, supply and demand balance, and environmental and economic benefits. A comparative analysis of 2017's power generation structure found that in the three scenarios, the proportion of thermal power is gradually decreasing, and the emphasis on new energy power generation is increasing, but there is a phenomenon of excess power.

A reference model is proposed and energy demand and supply assumptions are made for each sector to optimize the decarbonization model, and two decarbonization models are constructed for different levels of hydropower generation: the import model and the energy storage model, given the constraints between pumped storage plants and imported electricity. The import models require imported power support and a high reliance on biomass. The energy storage model requires the investment of a large number of pumped storage plants and has a high total cost.

Regardless of the investment cost, supporting the construction of pumped storage power plants as a flexible power source for large-scale energy storage technology can effectively improve the ability to absorb photovoltaic and wind power on-site and the technical and economic efficiency of transmission and transmission channels. However, through the comparative analysis of the economic benefits of the optimized model, under the same technical advantages and environmental benefits, the import model of importing clean electricity from neighboring provinces has the best cost-effectiveness and flexibility. Therefore, it is considered to adopt the import model to supplement the power transmission from Sichuan Province to other provinces, and finally realize a clean and decarbonized energy system. At this time, the energy structure is adjusted according to the maximum value of each capacity of the model in the three scenarios, and the installed power supply capacity and the transmission line capacity are basically the same.

At this time, the charging capacity of the pumped storage power station is 128.3 GW, the discharge capacity is 98.7 GW, and the storage capacity is 40581 GWh; the transmission line capacity is 64.6 GW. All 2030 optimization models can achieve clean energy substitution and zero carbon emissions compared to policy models. At the same time, the variable costs associated with fossil energy use are substantially reduced. Ultimately, with the reduced cost of future energy storage technologies, the total system cost will decrease overall and eventually be lower than the traditional 2030 policy model.

CRediT authorship contribution statement

Xiaokui Wang: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Olusola Bamisile:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Shuheng Chen:** Methodology, Supervision, Resources, Validation. **Xiao Xu:** Methodology, Resources, Validation. **Shihua Luo:** Data curation, Validation. **Qi Huang:** Data curation, Validation, Supervision. **Weihao Hu:** Methodology, Supervision, Resources, Validation.

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.

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References

[1] BP Statistical, Review of World Energy, 2019.
[2] M.Z. Jacobson, et al., 100% clean and renewable Wind, Water, and Sunlight (WWS) all-sector energy roadmaps for 53 towns and cities in North America, Sustain. Cities Soc. 42 (2018) 22–37.
[3] Z. Wang, et al., A Review and Comparative Analysis on Energy Transition in China's Three Emerging Urban Agglomerations, E3S Web of Conferences, 2021, p. 228.
[4] J.-L. Fan, et al., Optimization of China's provincial renewable energy installation plan for the 13th five-year plan based on renewable portfolio standards, Appl. Energy (2019) 254.
[5] Y. Hu, et al., Current status, challenges, and perspectives of Sichuan's renewable energy development in Southwest China, Renew. Sustain. Energy Rev. 57 (2016) 1373–1385.
[6] C.N. Zou, et al., Exploring petroleum inside source kitchen": shale oil and gas in Sichuan Basin, Sci. China Earth Sci. 63 (7) (2020) 934–953.
[7] X. Xu, et al., Look-ahead risk-constrained scheduling for an energy hub integrated with, Renew. Energy 297 (1) (2021), 117109.
[8] K. Vaillancourt, et al., Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework, Appl. Energy 195 (2017) 774–785.
[9] N. Khanna, et al., Energy and CO2 implications of decarbonization strategies for China beyond efficiency: modeling 2050 maximum renewable resources and accelerated electrification impacts, Appl. Energy 242 (2019) 12–26.
[10] L. Holstenkamp, What do we know about cooperative sustainable electrification in the global South? A synthesis of the literature and refined social-ecological systems framework, Renew. Sustain. Energy Rev. 109 (2019) 307–320.
[11] I. Sheikh, D. Callaway, Decarbonizing space and water heating in temperate climates: the case for electrification, Atmosphere 10 (8) (2019).
[12] E. Marrasso, C. Roselli, M. Sasso, Electric efficiency indicators and carbon dioxide emission factors for power generation by fossil and renewable energy sources on hourly basis, Energy Convers. Manag. 196 (2019) 1369–1384.
[13] D. Ponce de Leon Barido, et al., Opportunities for behavioral energy efficiency and flexible demand in data-limited low-carbon resource constrained environments, Appl. Energy 228 (2018) 512–523.
[14] M.A. Brown, Y. Li, Carbon pricing and energy efficiency: pathways to deep decarbonization of the US electric sector, Energy Efficiency 12 (2) (2018) 463–481.
[15] N. Aden, Necessary but not sufficient: the role of energy efficiency in industrial sector low-carbon transformation, Energy Efficiency 11 (5) (2017) 1083–1101.
[16] A. Grigoriev, V. Skorlygin, S. Grigoriev, Models of thermal processes for design optimization of power plants based on renewable energy sources and fuel cells, Therm. Sci. 23 (2019) 1225–1235, 2 Part B.
[17] M. Alves, R. Segurado, M. Costa, Increasing the penetration of renewable energy sources in isolated islands through the interconnection of their power systems. The case of Pico and Faial islands, Azores, Energy 182 (2019) 502–510.
[18] D.H. Vo, et al., The role of renewable energy, alternative and nuclear energy in mitigating carbon emissions in the CPTPP countries, Renew. Energy 161 (2020) 278–292.
[19] T. Burandt, et al., Decarbonizing China's energy system – modeling the transformation of the electricity, transportation, heat, and industrial sectors, Appl. Energy (2019) 255.
[20] K.X. Wang, et al., Enhancement of renewable energy penetration through energy storage technologies in a CHP-based energy system for Chongming, China, Energy 162 (2018) 988–1002.
[21] L. Bartolucci, et al., Hybrid renewable energy systems: influence of short term forecasting on model predictive control performance, Energy 172 (2019) 997–1004.
[22] J.J. Lian, et al., A review on recent sizing methodologies of hybrid renewable energy systems, Energy Convers. Manag. (2019) 199.
[23] X.Y. Tian, F.Q. You, Carbon-neutral hybrid energy systems with deep water source cooling, biomass heating, and geothermal heat and power, Appl. Energy 250 (2019) 413–432.
[24] L. Liu, et al., Multiple energy complementation based on distributed energy systems – case study of Chongming county, China, Appl. Energy 192 (2017) 329–336.
[25] M.R.N. Vilanova, A.T. Flores, J.A.P. Balestieri, Pumped hydro storage plants: a review, J. Braz. Soc. Mech. Sci. Eng. 42 (8) (2020).
[26] Q.H. Yu, et al., A review of compressed-air energy storage, J. Renew. Sustain. Energy 11 (4) (2019).
[27] K. Marnell, M. Obi, R. Bass, Transmission-scale battery energy storage

systems: a systematic literature review, Energies 12 (23) (2019).
[28] X.L. Fu, et al., Hybrid energy storage control strategy to curb wind power climbing, in: Proceedings of 2019 Ieee 8th Joint International Information Technology and Artificial Intelligence Conference (Itaic 2019), 2019, pp. 1825–1829.
[29] M. Uddin, et al., A review on peak load shaving strategies, Renew. Sustain. Energy Rev. 82 (2018) 3323–3332.
[30] P. Zhao, J. Wang, Y. Dai, Capacity allocation of a hybrid energy storage system for power system peak shaving at high wind power penetration level, Renew. Energy 75 (2015) 541–549.
[31] L. Sigrist, E. Lobato, L. Rouco, Energy storage systems providing primary reserve and peak shaving in small isolated power systems: an economic assessment, Int. J. Electr. Power Energy Syst. 53 (2013) 675–683.
[32] REN21, RENEWABLES, GLOBAL STATUS REPORT, 2021, 2021.
[33] I.H. Association, Advancing Sustainable Hydropower Annual Report 2021, 2021.
[34] Agency, I.A.E., Climate Change and Nuclear Power 2020. 2020.
[35] H.H. Rogner, et al., Keeping the nuclear energy option open, SSRN Electron. J. (2021).
[36] E.K. Gotske, M. Victoria, Future operation of hydropower in Europe under high renewable penetration and climate change, iScience 24 (9) (2021), 102999.
[37] T. Karier, J. Fazio, How hydropower enhances the capacity value of renewables and energy efficiency, Electr. J. 30 (5) (2017) 1–5.
[38] G.C.d. Andrade Furtado, et al., Using hydropower waterway locks for energy storage and renewable energies integration, Appl. Energy (2020) 275.
[39] K. Huang, et al., Improving complementarity of a hybrid renewable energy system to meet load demand by using hydropower regulation ability, Energy (2022) 248.
[40] B. Liu, et al., Optimal power peak shaving using hydropower to complement wind and solar power uncertainty, Energy Convers. Manag. (2020) 209.
[41] V.V. Markin, et al., Mini, Micro, and Small Hydropower Plants are Returning to the Market 54, 2020, pp. 494–499.
[42] U.N.I.D. Organization, World Small Hydropower Development Report, 2019.
[43] D. Šarauskienė, et al., Analysis of hydrologic regime changes caused by small hydropower plants in lowland rivers, Water 13 (14) (2021).
[44] T. Harlan, R. Xu, J. He, Is small hydropower beautiful? Social impacts of river fragmentation in China's Red River Basin, Ambio 50 (2) (2021) 436–447.
[45] I. Fantin-Cruz, et al., Further development of small hydropower facilities will significantly reduce sediment transport to the Pantanal Wetland of Brazil, Front. Environ. Sci. 8 (2020).
[46] R. Sousa, et al., Small hydropower plants as a threat to the endangered pearl mussel Margaritifera margaritifera, Sci. Total Environ. 719 (2020), 137361.
[47] Wang, H.X., et al. Compensation Model of Deep Peak Load Regulation of Thermal Power Units with Flexibility Reform.
[48] Y. Tang, et al., Optimizing the sizes of wind and photovoltaic power plants integrated into a hydropower station based on power output complementarity, Energy Convers. Manag. (2020) 206.
[49] G. Notton, et al., Operation of a photovoltaic-wind plant with a hydro pumping-storage for electricity peak-shaving in an island context, Sol. Energy 157 (2017) 20–34.
[50] R.S. Patwal, N. Narang, Optimal generation scheduling of pumped storage hydro-thermal system with wind energy sources, Appl. Soft Comput. 93 (2020).
[51] S.W. Xia, et al., Multitime scale coordinated scheduling for the combined system of wind power, photovoltaic, thermal generator, hydro pumped storage, and batteries, IEEE Trans. Ind. Appl. 56 (3) (2020) 2227–2237.
[52] S. Schismenos, et al., Humanitarian engineering and vulnerable communities: hydropower applications in localised flood response and sustainable development, Int. J. Sustain. Energy 39 (10) (2020) 941–950.
[53] M. Li, Q. Gong, C, H.J. Pan, Evaluation and strategic transformation of China's small hydropower under the goal of carbon neutrality, J. Beijing Univ. Technol.: Social Sci. Ed. 22 (2) (2022) 19.
[54] A. University, EnergyPLAN: Advanced Energy System Analysis Computer Model, 2010.
[55] S.R. Zhao, S.P. Cheng, Study on China's natural gas industry development strategy under the framework of international energy security cooperation-taking natural gas industry in Sichuan province as an example, in: 2012 International Conference on Management Science & Engineering, 2012, pp. 1686–1691.
[56] D.o.E.o. Statistics, Results of Reviews of Hydropower Resources in Sichuan Province, 2015 *edition).*, National bureau of statistics PRC, 2015.
[57] S.a.o. energy, Research on High Quality Development of Sichuan Energy, Sichuan association of energy, 2018.
[58] S.s. bureau, Sichuan Electric Power Yearbook 2018, Sichuan statistical bureau, 2018.
[59] C.Y. Tian, G.H. Huang, Y.L. Xie, Systematic evaluation for hydropower exploitation rationality in hydro-dominant area: a case study of Sichuan Province, China, Renew. Energy 168 (2021) 1096–1111.
[60] X.L. Li, et al., Analysis on the thermal balance and operational parameters for the district heating system with peak load boilers in heating substations, Energies 13 (23) (2020).
[61] P.A. Ostergaard, Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations, Appl. Energy 154 (2015) 921–933.
[62] D. Connolly, et al., A review of computer tools for analysing the integration of renewable energy into various energy systems, Appl. Energy 87 (4) (2010) 1059–1082.
[63] M.G. Prina, et al., Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning, Appl. Energy 235 (2019) 356–368.
[64] D. Connolly, et al., The first step towards a 100% renewable energy-system for Ireland, Appl. Energy 88 (2) (2011) 502–507.
[65] D. Connolly, H. Lund, B.V. Mathiesen, Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union, Renew. Sustain. Energy Rev. 60 (2016) 1634–1653.
[66] D. Viesi, et al., Integrated and dynamic energy modelling of a regional system: a cost-optimized approach in the deep decarbonisation of the Province of Trento (Italy), Energy (2020) 209.
[67] R. Ramos, R. Castro, Modeling renewable energy integration in the 2030 Portuguese power system: the role of energy storage, J. Electrochem. Energy Conversion Storage 17 (1) (2020).
[68] A.D. Korberg, I.R. Skov, B.V. Mathiesen, The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark, Energy (2020) 199.
[69] O. Bamisile, et al., An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030, Energy (2020) 197.
[70] G.G. Dranka, P. Ferreira, Planning for a renewable future in the Brazilian power system, Energy 164 (2018) 496–511.
[71] W. You, et al., Technical and economic assessment of RES penetration by modelling China's existing energy system, Energy 165 (2018) 900–910.
[72] H. Zhang, et al., Decarbonizing a large City's heating system using heat pumps: a case study of Beijing, Energy (2019) 186.
[73] W. You, et al., Technical and economic assessment of RES penetration by modelling China's existing energy system, Energy 165 (2018) 900–910.
[74] M.F. Tahir, et al., Integration of different individual heating scenarios and energy storages into hybrid energy system model of China for 2030, Energies 12 (11) (2019).
[75] D.o.E.o. Statistics, in: N.b.o.s. PRC (Ed.), China Energy Statistical Yearbook 2018, China Statistical Press, Beijing, 2018.
[76] Q. Wang, Yi, Energy data, 2018, Innovat. Green Dev. Prog. (2018).
[77] W.M. Xiong, et al., Heat roadmap China: new heat strategy to reduce energy consumption towards 2030, Energy 81 (2015) 274–285.
[78] G. Chen, Z. Liang, Y. Dong, Analysis and reflection on the marketization construction of electric power with Chinese characteristics based on energy transformation, Proceedings of the CSEE 40 (2020) 369–379, 02.
[79] T.p.s.g.o. Sichuan, Sichuan's 13th Five-Year Plan for Energy Development, 2017. Chengdu city.
[80] S.a.o. energy, Research on Some Major Issues of Medium and Long-Term Power Development in Sichuan Province, Sichuan association of energy, Chengdu city, 2018.
[81] energy, S.a.o., *Study On Wind-PV-Hydro Complementation And Development Layout In Sichuan Province*. 2018, Sichuan Association of Energy: Chengdu city.
[82] C.E.T.R. Institute, World and China Energy Outlook in 2050, CNPC Economics&Technology Research Institute, 2020.
[83] Q.Y. Zhu, et al., Analyzing the sustainability of China's industrial sectors: a data-driven approach with total energy consumption constraint, Ecol. Indicat. (2021) 122.
[84] T. Wang, B.Q. Lin, Fuel consumption in road transport: a comparative study of China and OECD countries, J. Clean. Prod. 206 (2019) 156–170.
[85] Commission, R.G.o.E.R.I.N.D.A.R., Research on the Energy Saving Targets of the Transportation Sector in the 13th Five-Year Plan and 2030, Energy Research Institute National Development And Reform Commission, 2017.
[86] P.J. Zhao, J.J. Diao, S.X. Li, The influence of urban structure on individual transport energy consumption in China's growing cities, Habitat Int. 66 (2017) 95–105.
[87] S.P.P.s. Government, Urban System Planning of Sichuan Province (2014-2030), 2016.
[88] A. Bonati, et al., The integration of exergy criterion in energy planning analysis for 100% renewable system, Energy 174 (2019) 749–767.
[89] Xiao, X., et al., Optimal operational strategy for an offgrid hybrid hydrogen/electricity refueling station powered by solar photovoltaics. J. Power Sources. 451.
[90] K. Vaillancourt, O. Bahn, A. Levasseur, The role of bioenergy in low-carbon energy transition scenarios: a case study for Quebec (Canada), Renew. Sustain. Energy Rev. 102 (2019) 24–34.
[91] A. O'Connell, et al., Considerations on GHG emissions and energy balances of promising aviation biofuel pathways, Renew. Sustain. Energy Rev. 101 (2019) 504–515.
[92] J. Kester, et al., Public Perceptions of Electric Vehicles and Vehicle-To-Grid (V2G): Insights from a Nordic Focus Group Study, 74, Transportation Research Part D-Transport and Environment, 2019, pp. 277–293.
[93] B. Cosic, G. Krajacic, N. Duic, A 100% renewable energy system in the year 2050: the case of Macedonia, Energy 48 (1) (2012) 80–87.
[94] Group, S.E.P.R., EnergyPLAN Cost Database, in *Version 4.0*. 2018, Aalborg University: Aalborg.
[95] B. Yang, Y. Hu, W. Huang, Research on the green pricing method of hydropower based on social benefits and environmental benefits, China Rural Water and Hydropower (1) (2017) 194–198.
[96] J. Xu, D. Dong, Research on the rolling development of new energy investment business under the national macro-control policy, Ch. Electric Power Enterprise Manag. (28) (2020) 52–56.