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Carbon Neutrality in Provincial Energy System: a Case Study of 2060 Sichuan Province

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ABSTRACT

Worldwide global warming has become a crisis for all human beings. As the largest carbon emitter in the world, China has committed to reducing its carbon emissions to net-zero before 2060. Considering the fact that the energy system is the largest emission source in China, reducing carbon emissions from burning fossil fuels has significant meaning for this country. This paper establishes an hourly low-carbon energy system planning model, which jointly considers load curve and renewable energy output characteristics by using mixed-integer linear programming method. Also, the model creatively introduces the function of seasonal regulation of hydro power stations into the planning model of the low-carbon energy system. Sichuan Province, one of the largest suppliers of renewable energy in China, is selected as a case study. The case study discusses the possibility of realizing a carbon-neutral power energy system in Sichuan Province in 2060 under two scenarios, lower demand and higher demand. Under the scenario of lower load estimation, that is, when the annual load is 634.8 TWh, Sichuan can reduce carbon emissions to zero at a reasonable annual cost of 94.4 billion CNY. The high-load scenario assumes that all potential renewable energy has been explored in the province. This scenario can generate 878.4 TWh of clean electricity every year, with an annualized cost of 142.5 billion CNY.

Keywords: Low carbon power system planning model; Carbon neutrality; Optimal operation solution; Sichuan

NONMENCLATURE

Abbreviations	
O&M	Operation and maintenance
CNY	China yuan
CCS	Carbon capture and storage
PV	Photovoltaic
WF	Wind farm

1. INTRODUCTION

Climate change is a major and urgent global challenge towards mankind. In 2020, China stated that it would increase its nationally determined contributions, striving to peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 [1].

There are still challenges and difficulties in achieving this ambitious goal directly on national scale. First, China's carbon emissions mainly come from the energy system, accounting for 86.9% of total carbon emissions[2]. Existing studies have proposed different models to reduce carbon emissions from the power sector, but the cost could reach more than 50 trillion CNY [3]. Such a huge investment requires a staggering amount of resources. Given the fact that China is still a developing country, it is difficult for stakeholders to commit so much money to address climate issues when such investments are likely to yield greater benefits elsewhere.

While reducing carbon emissions from national power system is expensive, the cost of establishing a low-carbon (or even zero-carbon) energy system based on local renewable energy may be acceptable in some provinces. Besides, these provinces can even export surplus renewable energy to other regions to reduce the carbon emission level of the entire Chinese power system. Although some studies have taken these provinces' strengths, i.e., abundant local renewable energy, into account when modelling national power system, there is a lack of research on whether these provinces can achieve carbon neutralization of their own power system.

In this paper, a carbon-neutral power system planning model is established by mixed-integer linear programming. Under the premise of minimum carbon emission, the model can optimize the installed capacity of different generation technologies. Under two different scenarios, the carbon-neutral power system deployment of Sichuan, a province with abundant renewable resources, is presented as a case study. Scenario 1 refers to 'low demand', which assumes that the current level of external power transmission in Sichuan Province remains unchanged, that is, the annual export of 150TWh to other provinces, leading to a total provincial load of 634.8 TWh per year. The results show that in this scenario, the annualized cost of realizing a provincial carbon-neutral power system in Sichuan is 94.4 billion CNY. Scenario 2 means 'high demand'. To be specific, it suggests that all potential renewable energy of Sichuan Province will be explored, and a total of 878.4 TWh of clean electricity can be generated. Compared with scenario 1, the annual cost of scenario 2 may rise to 142.5 billion CNY.

2. METHODOLOGY

This section describes a series of sub-models that together simulate future regional power system, including the objective, generator modelling and constraints presentation, which are as follows:

2.1 objective function

The objective of the model is to minimize the total cost of the power system on the premise of minimizing the total carbon emissions.

2.1.1 The objective:

$$\begin{gathered} min \;\; C_{total} \\ s.t. min \;\; C_{CE} \end{gathered} \tag{1}$$

where:

$$C_{CE} = \sum_{s_t=1}^{S^T} D_s \sum_{t=1}^{T} \sum_{g=1}^{G} c_k \gamma_g P_{g,s}^t \Delta t \tag{2}$$

where c_k is the CO_2 emission cost per kg of CO_2 and γ_g denotes the equivalent emission coefficients (kg/kWh) of the consumed g_{th} type of energy. s_t is the index of representative time periods and S^T denotes the total number of representative time periods, which is the number of seasons in this paper. D_s is the number of days that the s_{th} period can represent. g is the index for the input energy types from outside utilities, G is the total number for the input energy types.

Considering the fact that there can be more than one generation technology combination that achieving this objective, this paper then finds the optimal one with lowest cost, C_{Total}. C_{Total} contains the capital cost C_C, the energy cost C_E, and the maintenance cost C_M.

$$C_{Total} = C_C + C_E + C_M \tag{3}$$

2.1.1 The capital cost $\boldsymbol{C_C}$

The annualized cost of a component is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component. It can be formulated as [4]:

$$C_C = \sum_{k=1}^{K} \frac{r(r+1)^Y}{(r+1)^Y-1} \theta_k V_k \cdot \alpha_k \tag{4}$$

where k is the index of candidate devices including energy converters and renewable energy generators. K is the total number of candidate devices, r denotes the discount rate, Y denotes the estimated life time of device k , V_k and θ_k refer to the capacity and the capital cost of unit capacity for device k, respectively. α_k is a binary variable which corresponds to the selection of device k, if α_k = 1, device k is selected.

2.1.2 The energy cost $\boldsymbol{C_E}$

The energy cost refers to the spending on purchasing energy from the system outside, such as importing gas and electricity from the grid. The energy cost can be expressed as follows:

$$C_E = \sum_{s_t=1}^{S^T} D_s \sum_{t=1}^{T} \sum_{g=1}^{G} \psi_{g,s}^t P_{g,s}^t \Delta t \tag{5}$$

where $\psi_{g,s}^t$ and $P_{g,s}^t$ denote the energy price and input power of the model at time t, for the g_{th} type of energy and at the s_{th} time period. T is the total number of time slots in one day. Δt means one hour in this paper.

2.1.3 The maintenance cost $\boldsymbol{C_M}$

Maintenance costs are any expenses incurred by a business to keep an asset, such as solar PV panel, wind turbine and thermal power plant, etc., in good working condition. The maintenance cost can be expressed as follows:

$$C_M = \sum_{s_t=1}^{S^T} D_s \sum_{t=1}^{T} \sum_{k}^{K} \lambda_k \overline{P_{k,e}^{out}} \Delta t \tag{6}$$

where λ_k and $\overline{P_{k,e}^{out}}$ are the unit maintenance cost and maximum output power of device k, respectively.

2.2 Constraints:

2.2.1 Device output and constraints

The general device input-output relationship was introduced in reference [3], which is required to select the facility first. The candidate devices mainly include energy converters and renewable energy generators. The electrical storage, due to safety reason, it is not involved in our model. The output-input coupling relationship of an energy converter can be expressed as:

$$P_{k,\mathrm{e}}^{out,t} = \eta_k^t P_{k,\mathrm{g}}^{in,t} \tag{9}$$

Where $P_{k,e}^{out,t}$ and $P_{k,g}^{in,t}$ denote the output power/input power of energy converter k at time slot t . η_k^t denotes the energy conversion efficiency of converter k at time slot t

The output power of energy converters and renewable generators should keep within their capacity constraints. Their selection is represented by binary variables:

$$\alpha_k \cdot \underline{P_{k,\mathrm{e}}^{out}} <= P_{k,\mathrm{e}}^{out,t} <= \alpha_k \cdot \overline{P_{k,\mathrm{e}}^{out}} \tag{10}$$

where $\underline{P_{k,e}^{out}}$ denotes the minimum output power of device k, respectively.

For renewable energy units, the capacity is less than the regional resource limit,

$$\alpha_k \cdot \overline{P_{k,e}^{out}} < P_j^s \tag{11}$$

where P_j^s is the amount of regional renewable source j.

2.2.2 Demand balance constraint

In addition, the total generation should equal the total demand:

$$\sum_{k=1}^{K} P_{k,\mathrm{e}}^{out,t} = D_t \tag{12}$$

where $\sum_{k=1}^{K} P_{k,\mathrm{e}}^{out,t}$ is the total power generation from all generators; D_t is the total demand at time *t*.

2.2.3 Minimum up down constraints.

For conventional units, e.g., Gas-CCS power station and biomass power station, they need to remain operational (or non-operational) for a certain time period at least if it has started-up (or shut-down) at the previous time point j respectively. In other words, the sum of operational state $u_{t,i}$ must be greater than or equal to the minimum up time L_i of each unit, and the unit's non-operational time $(1-u_{t,i})$ (after being shut-down), must be greater than or equal to the minimum down time F_i of each unit. Under such an assumption, the minimum up (down) constraints are given below [5]:

$$L_i = Min\{T, j + UT_i - 1\} \tag{13}$$

$$\sum_{t=k}^{L_i} u_{t,i} \geq \sum_{t=k}^{L_i} \left(u_{k,i} - u_{k-1,i}\right) \tag{14}$$

$$F_i = Min\{T, j + DT_i - 1\} \tag{15}$$

$$\sum_{t=k}^{F_i} \left(1 - u_{t,i}\right) \geq \sum_{t=k}^{F_i} \left(u_{k-1,i} - u_{k,i}\right) \tag{16}$$

where $U_{i,t}$ is a binary variable that use 0 and 1 to indicate start-up state and stop state, respectively; the UT_i and DT_i are minimum up (down) time of generating unit i, respectively. While j is the specific timepoint from beginning to the total modelling horizon, T.

2.2.4 System reverse constraint

The system reserve requirement R_{rate} was assumed to be 10% of the demand [5].

$$\sum_i^I u_{t,i} \overline{P_{k,\mathrm{e}}^{out}} \geq D_t(1 + R_{rate}) \tag{17}$$

where $\overline{P_{k,e}^{out}}$ is the maximum generation capacity from generator i.

2.2.5 Ramping rate.

The output variation level of each conventional unit is restricted by ramp rate constraints, both up and down.

$$P_i^{\mathrm{down}} < P_{k,\mathrm{e}}^{out,t} - P_{k,\mathrm{e}}^{out,t-1} < P_i^{\mathrm{up}} \tag{18}$$

P_i^{down} and P_i^{up} are ramp-down rate and ramp-up rate of unit i.

2.2.6 hydro power plant constraints

Hydro power not only needs to meet device constraints and the ramp rate constraint above, but also needs to meet the water constraints. For normal hydro power plant, its daily output $\sum_{t=1}^{N_{tm}} P_{hy,j}$ need to equal to or less than the volume of water arriving at the same day. For seasonal regulated and annual regulated hydro power stations, their water storage capacity can enable them to break through this limit. Their electricity generation can be optimized according to the amount of water thought several seasons or even the whole year. No matter which kind of hydro power stations, it is assumed that their storage capacities bottom at the end of winter.

$$0 \leq \sum_{t=1}^{N_{tm}} P_{hy,j} \leq \sum_{t=1}^{N_{tm}} E_{hy}^m \tag{19}$$

where $P_{hy,j}$ is the power output from station, j. The N_{tm} refers to its regulation period, for normal power plant, it is one day. For seasonal and yearly regulated power plant, it is nine months and one year, respectively. E_{hy}^m is the total hydro energy available for one month.

3. CASE STUDY

This study chooses Sichuan province to prove the effectiveness of the model. As a western province in China, Sichuan enjoys rich hydro power resources and has become one of the largest clean energy exportation areas in China.

The optimization in this study is conducted on an hourly basis for a typical day of each season, taking into account daily and seasonal fluctuations in energy supplies and demands.

3.1 Demand data:

Electricity consumption for 2060 is magnified based on existing annual consumption. According to reference [6], the power demands of Sichuan Province in 2020 and 2060 are projected as 231.5TWh and 503.4 TWh respectively. The case study applies the 2020 typical daily consumption data provided by the local system operator and expand it to the provincial level.

3.2 Transmission capacity in Sichuan:

Except for domestic electricity consumption, Sichuan province provides around 150 TWh of electricity to other areas in China throughout existing transmission line capacity of 25,000 MW. It is expected that the transmission capacity between Sichuan and other provinces would grow to 64,600 MW in 2060 [11].

3.3 Wind farm and solar PV power output:

In this work, the historical capacity factor for PV and WF from reference[7], instead of wind speed or solar irradiation, are directly used as inputs to the model.

It is estimated that the actual wind energy resources that can be used in Sichuan are more than 20 GW. In addition, preliminary statistics also show that more than 40 GW of solar energy can be used in this province[8]. Fig.1 illustrates the typical renewable energy capacity factor in Sichuan.

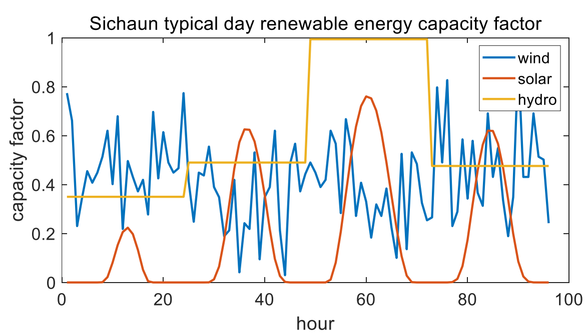

Fig. 1. Renewable energy capacity factor in Sichuan

3.4 Hydro resource in Sichuan:

The Sichuan hydro power output comes from Sichuan Water Conservancy Department[9]. The average level of hourly power output for each season is used as model input. According to [9], Sichuan has developed 70% of its tremendous hydro power resources (148 GW), of which 66% and 24% of hydro power stations are daily regulated and seasonal regulated respectively, while the remaining 10% have the annual regulation capacity[10].

3.5 Biomass resource in Sichuan:

According to research, the annual biomass capacity of Sichuan is equivalent to 20 million tons of standard coal [8].

3.6 Thermal power in Sichuan:

At present, there have been difficulties in coal mining and transportation in Sichuan, but there is plenty of natural gas resource. Considering the actual situation, gas power plant plus CCS in Sichuan Province is an important means to reduce carbon emissions. According to [3], the CCS efficiency is assumed as 90%.

3.7 Power generation technology parameter:

The cost of power generation technology includes construction investment cost, O&M cost and fuel consumption cost. This study uses the data from references [3] and [12] as the model input. The maximum utilization capacity of each technology is set according to the proved reserves of Sichuan. Moreover, the interest rate in this paper is assumed as 4.5%.

Table 1. Generation technology cost

Technology	Gas CCS	Hydro	Wind	Solar	Biomass
Capital cost (CNY/kW)	6723	11360	7719	7258	11186
O&M cost (percent of the capital cost (%))	3.7	0.9	2.9	1	2
Unit size (GW)	1	1	1	1	1
Maximum number	10	145	20	40	10
Lifetime(year)	30	30	30	30	30

Table 2. Generation technical characteristics

Technology	Gas CCS	Biomass
Min stable power (%)	35	35
Min up/down time (hrs)	4	4
Ramp rate (MW/h)	900	1000
Efficiency	0.61	0.46

Table 3. Generation carbon emission factor and fuel cost

Energy Source	Price (CNY 2015/MWh)	CO_2 factor (tons/MWh)
Natural gas	275	0.183
Biomass	214	0

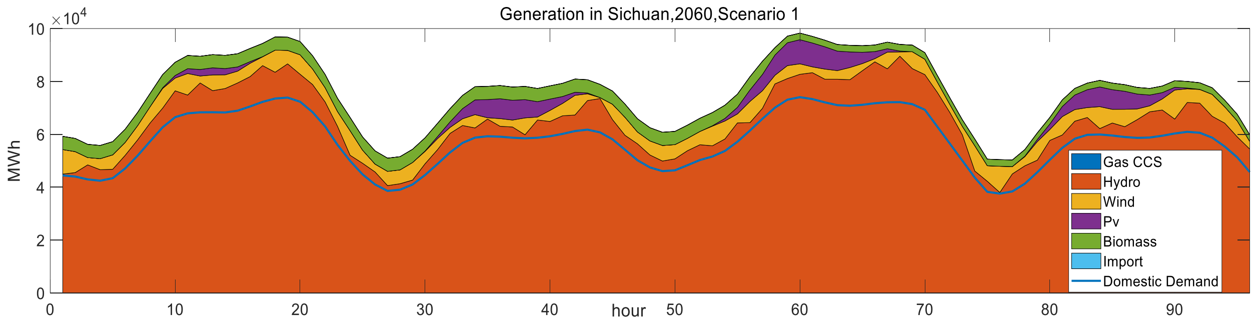

Fig. 2. Sichuan Power Generation in 2060, Scenario 1.

4. RESULTS

4.1 Scenario 1. Lower demand: Exportation constant

At present, Sichuan delivers about 150 TWh of electricity outside every single year. Scenario 1 attempts to minimize carbon emissions while keeping the electricity transmission volume unchanged. It turns out that achieving this goal requires integrating wind / hydro power / solar power generation into the system to replace existing coal-fired and gas-fired generation units.

Table 4. Scenario 1 results

Scenario 1	2060 capacity	2019 capacity [3]	Annualized cost (CNY)
Gas CCS (GW)	5.00	0.82	3.06*10^09
Hydro (GW)	100.00	79.00	6.97*10^10
PV (GW)	15.00	1.80	7.77*10^09
WF(GW)	15.00	3.00	1.04*10^10
Biomass (GW)	5.00	0.50	3.48*10^09

As shown in Fig. 2, Sichuan Province can fully achieve zero-carbon operation of the power system by 2060. Due to the existence of seasonally and yearly regulated hydro power stations, Sichuan no longer needs to rely on external power supply in winter. The main forces of power supply are hydro power, PV, wind power and biomass. Moreover, due to the system reserve constraint, the technology combination in scenario 1 is still equipped with 5GW natural gas + CCS, but does not need to generate electricity under normal circumstances.

This paper believes that the cost of such a power system will be as high as 94.4 billion CNY, of which 88% is used to invest in renewable power generation technologies. And the installed capacity of renewable energy accounts for 90.1% of the total installed capacity. More detailed information is given in Table 4, which gives the installed capacities and extra annualized costs for different technologies. The installed capacities of photovoltaic and wind are 15 GW each, but the annualized cost of PV is higher than wind power, since the former one has a much lower operation and maintenance cost. The installed capacities of hydro power and biomass are 100 GW and 5 GW respectively, which are the biggest and the tiniest among all renewable generation technologies, individually.

4.2 Scenario 2. Higher demand: maximizing electricity exploration and exportation.

Scenario 2 shows the scenario of making full use of Sichuan renewable energy and maximizing electricity exploration. The scenario actually simulates the largest clean energy generation capacity in Sichuan Province. As shown in Fig. 3, the annual maximum hourly load of Sichuan Province (considering the exportation) in scenario 2 is 128.46 GWh, which is higher than that of scenario 1 by 54.41 GWh.

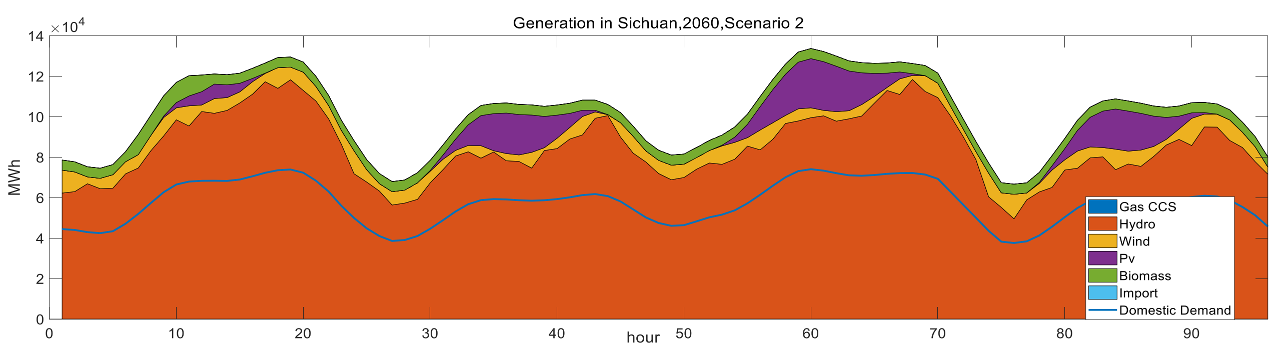

Fig. 3. Sichuan Power Generation in 2060, Scenario 2

At the same time, as shown in Table 5, the installed capacity of PV, wind power and hydro power reached 40 GW, 20 GW and 145 GW respectively. Basically, all the proven renewable energy sources have been developed. At the same time, the natural gas + CCS unit is no longer required to bear the reserve load, the system reserve load is mainly borne by hydro power and biomass. Finally, the life cost of the system increases from 94.4 billion CNY in scenario 1 to 142.5 billion CNY.

Table 5. Scenario 2 results

Scenario 2	2060 capacity	2019 capacity [3]	Annualized cost (CNY)
Gas CCS (GW)	0	0.82	0
Hydro (GW)	145.00	79.00	1.01*10^11
PV (GW)	40.00	1.80	2.07*10^10
WF(GW)	20.00	3.00	1.39*10^10
Biomass (GW)	10.00	0.50	6.99*10^09

5. CONCLUSION AND FUTURE WORK

This study establishes an energy system planning model towards the optimal design of a provincial-level power system. The model selects the proper generation technologies from a series of candidates and determines their optimum size with optimal operational strategy.

It is worth noting that the model especially considers the impacts of hydro power stations with different regulation capacities on power system planning. To prove the effectiveness of the model, a 2060 carbon-neutral power system for Sichuan province under two scenarios has been proposed. The first scenario is to simulate the lower load of Sichuan Province in 2060 and keep Sichuan's future exports to the region the same as nowadays. The establishment of a carbon-neutral power system requires an annual investment of 94.4 billion CNY. Scenario 2 discusses the total amount of clean electricity that can be generated when the renewable energy in Sichuan Province is fully developed. This scenario points out with an annual investment of 142.5 billion CNY, the total power generation from renewable energy of Sichuan Province can be as high as 878.4 TWh in 2060.

The main assumptions and limitations of the model are as follows: firstly, this work assumes all types of hydro power stations, i.e., daily-regulated, seasonal-regulated and yearly regulated, with identical construction costs and other operating costs. Moreover, this work also simply averages monthly hydrological information to hourly level and use it to model hydro power station generation.

These two assumptions greatly influence the results of the model. In the future, with further research, the accuracy of the model is expected to be greatly improved if relevant detailed hydrological and cost information is provided.

6. ACKNOWLEDGEMENT

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