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Potential of Curtailed Renewable Power Utilization Under Carbon Neutrality – A China Case Study

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ABSTRACT

With the recently announced 2060 carbon neutrality goal by China, high penetration of renewable resources in power sector can be expected. However, the intermittent nature of wind and solar energies requires the deployment of dispatchable technologies and also raises the problem of power curtailment. In this work, a case study on China's power sector in 2018 is conducted as if carbon neutrality was to be enforced. Both fossil fuels and renewable resources are utilized for power supply to match hourly demand profile at minimum system cost. Moreover, the amount of power curtailment is estimated from the optimal carbon neutral power mix. Leveraging on the concept of energy-chemical nexus, the potential of producing green methanol and ammonia in China from hydrogen via water electrolysis with curtailed power is investigated.

Keywords: renewable energy, carbon neutrality, power curtailment, energy-chemical nexus, green methanol, green ammonia

NONMENCLATURE

Abbreviations	
GHG	Greenhouse gas
CCS	Carbon capture and storage
Symbols	
h	Index for hours
j	Index for technologies
x_j	Capacity of technology j
$y_{h,j}$	Operation of technology j in hour h
R	Discount rate
LT_j	Facility lifetime of technology j
CAPEX_j	Capital cost of technology j
FOPEX_j	Fixed cost of technology j
VOPEX_j	Variable cost of technology j
DM_h	Electricity demand in hour h
$\mathrm{CF}_{h,j}$	Capacity factor of technology j in hour h
EFF_j	Fuel efficiency of technology j
POT_j	Potential of technology j
CAPEM_j	GHG emission of technology j in construction phase
POPEM_j	Positive GHG emission of technology j in operation phase
NOPEM_j	Negative GHG emission of technology j in operation phase

1. INTRODUCTION

With the most recent announcement at the 75th United Nations General Assembly held in September 2020, China has reaffirmed its determination in fighting climate change and committed to peak CO_2 emission before 2030 and achieve net zero greenhouse gas (GHG) emission (i.e., carbon neutrality) by 2060 [1]. Currently, power sector accounts for more than 45% of China's total CO_2 emission due to its heavy reliance on coal as energy sources [2], highlighting the necessity of energy transformation towards renewable resources. However, given the discontinuous and fluctuating nature of wind and solar generation, the problem of power curtailment could become more significant with increasing share of those intermittent technologies in power mix. The concept of energy-chemical nexus provides an opportunity for curtailed power utilization in chemical

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synthesis [3]. For concreteness, methanol and ammonia are selected as the representative products of chemical sector to quantitatively access the potential of utilizing curtailed power for green chemicals production.

2. METHODOLOGY

2.1 Renewable Potential

In this work, the potential of economically viable hydropower in China is obtained from [4] with its capacity factor calculated from the current utilization hours in [5]. For wind and solar energy, their installation potentials as well as hourly capacity factors are collected from [6,7], respectively. The utilizable potential of biomass depends on the collection rate of relevant resources and the anticipated long-term value for 2050 from [8] is used.

Besides renewable potential, the typical day load characteristics are obtained from [9] which can be used to disaggregate power demand to hourly scale. The remaining parameters, including capital, fixed and variable costs, construction and operation phase emissions, as well as electricity, methanol and ammonia demands are directly inherited from our previous work [10] with details provided in its Key Resources Table.

2.2 Optimization Model

In this work, a China case study for the year of 2018 is conducted. Electricity can be generated from fossil fuels including coal and natural gas, with or without carbon capture and storage (CCS). Renewable resources such as hydro, wind, solar and biomass are also involved, with biomass-CCS serving as the negative emission technology. Except for the aforementioned renewable potentials, the current values in 2018 are assumed for all other parameters.

The optimization model minimizes total annual cost which consists of the following three components,

$$\min_{x,y} \sum_j \frac{\mathrm{R}}{1-(1+\mathrm{R})^{-\mathrm{LT}_j}} (\mathrm{CAPEX}_j) x_j + \sum_j (\mathrm{FOPEX}_j) x_j + 365 \sum_{h,j} (\mathrm{VOPEX}_j) y_{h,j}$$

where decision variables x_j and $y_{h,j}$ represent the capacity of technology j and operation of technology j in hour h, respectively. R is the discount factor taken to be 8% in this work and LT_j is the facility lifetime of technology j. CAPEX_j, FOPEX_j and VOPEX_j denote the capital, fixed and variable costs of technology j, respectively. Electricity demand must be satisfied every hour, so that

$$\sum_j y_{h,j} \geq \mathrm{DM}_h \quad \forall h$$

where DM_h is the typical day electricity demand in hour h. Note that "larger than or equal to" sign is used in the equation above to account for any possible curtailment. For coal, natural gas and biomass-based technologies, they are considered dispatchable so flexible generation profiles can be arranged while no flexibility is allowed for nuclear power.

$$y_{h,j} \leq x_j \quad \forall h, j \in \left\{ \begin{matrix} \text{coal, coal-CCS,} \\ \text{natural gas, natural gas-CCS,} \\ \text{biomass, biomass-CCS} \end{matrix} \right\}$$

$$y_{h,\,\text{nuclear}} = x_{\text{nuclear}} \quad \forall h$$

In this work, hydropower is assumed to provide baseload so that constant generation over the day is modeled. For wind and solar power, hourly capacity factors are incorporated to account for variable weather conditions.

$$y_{h,\,\text{hydro}} = (\mathrm{CF}_{\text{hydro}}) x_{\text{hydro}} \quad \forall h$$

$$y_{h,j} = (\mathrm{CF}_{h,j}) x_j \quad \forall h, j \in \{\text{wind, solar}\}$$

The annual availabilities of coal, natural gas and nuclear fuel are set to equal those in 2018 while full potentials of renewable resources are considered in the model. Note that hydro, wind and solar potentials are expressed in capacity units while others are represented by the availability of respective fuels.

$$365 \sum_{h,j \in \{\text{coal, coal-CCS}\}} \frac{y_{h,j}}{\mathrm{EFF}_j} \leq \mathrm{POT}_{\text{coal}}$$

$$365 \sum_{h,j \in \{\text{natural gas, natural gas-CCS}\}} \frac{y_{h,j}}{\mathrm{EFF}_j} \leq \mathrm{POT}_{\text{natural gas}}$$

$$365 \sum_h \frac{y_{h,\,\text{nuclear}}}{\mathrm{EFF}_{\text{nuclear}}} \leq \mathrm{POT}_{\text{nuclear}}$$

$$x_j \leq \mathrm{POT}_j \quad \forall j \in \{\text{hydro, wind, solar}\}$$

$$365 \sum_{h,j \in \{\text{biomass, biomass-CCS}\}} \frac{y_{h,j}}{\mathrm{EFF}_j} \leq \mathrm{POT}_{\text{biomass}}$$

Finally, the carbon neutrality goal requires net zero GHG emission.

$$\sum_{j} \frac{1}{\mathrm{LT}_j} (\mathrm{CAPEM}_j) x_j + 365 \sum_{h,j} (\mathrm{POPEM}_j) y_{h,j} + 365 \sum_{h,j} (\mathrm{NOPEM}_j) y_{h,j} = 0$$

where CAPEM_j denotes the GHG emission of technology j in construction phase and is amortized over the facility lifetime. POPEM_j and NOPEM_j are the positive and negative GHG emissions of technology j in operation phase, respectively.

3. RESULTS AND DISCUSSION

3.1 Technology Mix

Solving the optimization model formulated in previous Section results in a minimum annual cost of 4.42 trillion RMB under carbon neutrality. The corresponding technology mix for power generation is shown in Fig. 1 (B). For comparison, the current power mix in 2018 is obtained from [5] and plotted in Fig. 1 (A).

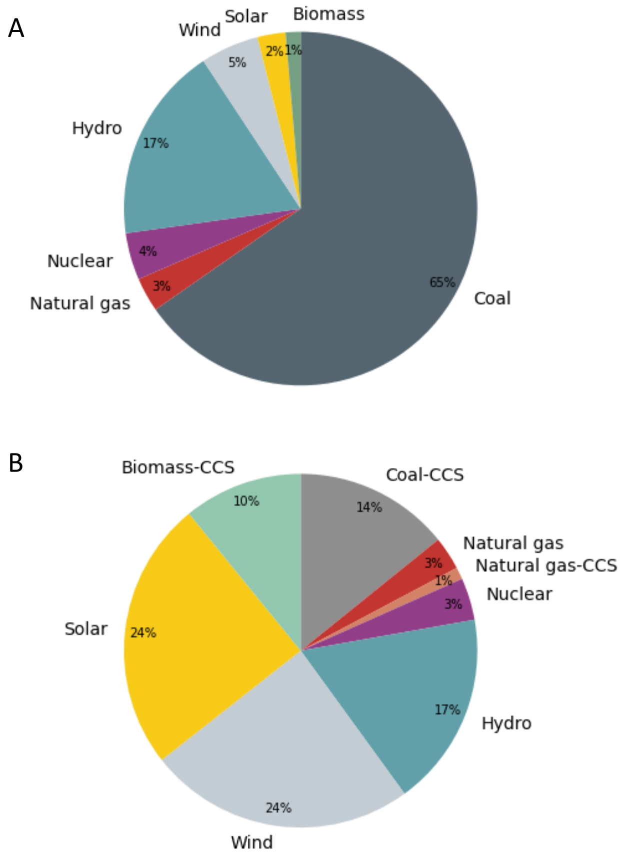

Fig. 1. Current (A) and carbon neutral (B) power mix for China in 2018

A significant reduction in the share of fossil fuels in power sector under carbon neutrality can be observed in Fig. 1, with coal-fired power plants completely phased out or replaced by CCS integrated counterparts. For renewable energies, the share of hydropower remains constant while that of wind and solar booms, together contributing to almost half of total generation. As a negative emission technology, biomass-CCS is adopted to neutralize any positive GHG emission from other technologies.

3.2 Curtailed Power Utilization

Given the anticipated vast exploitation of renewable resources for electricity generation, the issue of power curtailment arises. In particular, Fig. 2 shows the hourly electricity demand and supply for a typical day in 2018 under carbon neutrality obtained from the optimization model.

From Fig. 2, oversupply of electricity can be observed in the early afternoon, which would aggregate into an annual power curtailment of 143.8 TWh if not otherwise utilized. As suggested by the concept of energy-chemical nexus [3], the curtailed power can be potentially used for water electrolysis to supply hydrogen in chemical synthesis. Methanol and ammonia are selected as the representative chemicals in this work considering their large demands in China and the technology maturity of directly producing those chemicals from hydrogen. The fact that currently coal-to-ammonia and coal-to-methanol processes respectively contribute to 41.3% and 21.0% of total CO_2 emission from coal chemistry in China [11] also rationalizes such selection.

With a conversion factor of 53 kWh/kg H_2 [12], the curtailed power can supply 2.7 Mt hydrogen to chemical sector. In 2018, methanol and ammonia demands in China are 62 Mt and 56 Mt [10], respectively, which converts to a maximum consumption of 21.5 Mt hydrogen with stochiometric coefficients of 0.188 kg H_2/kg CH_3OH and 0.176 kg H_2/kg NH_3. Therefore, if carbon neutrality was to be enforced in 2018, curtailed renewable power would have the potential of replacing as mush as 12.6% of conventional fossil-based methanol and ammonia production in China. Using the average carbon intensity of current methanol and ammonia production in China [11], power sector, via curtailment utilization, can contribute to an emission reduction of at most 60 Mt CO_2 in chemical sector.

4. CONCLUSION

In this work, the potential of utilizing curtailed renewable power under the context of carbon neutrality

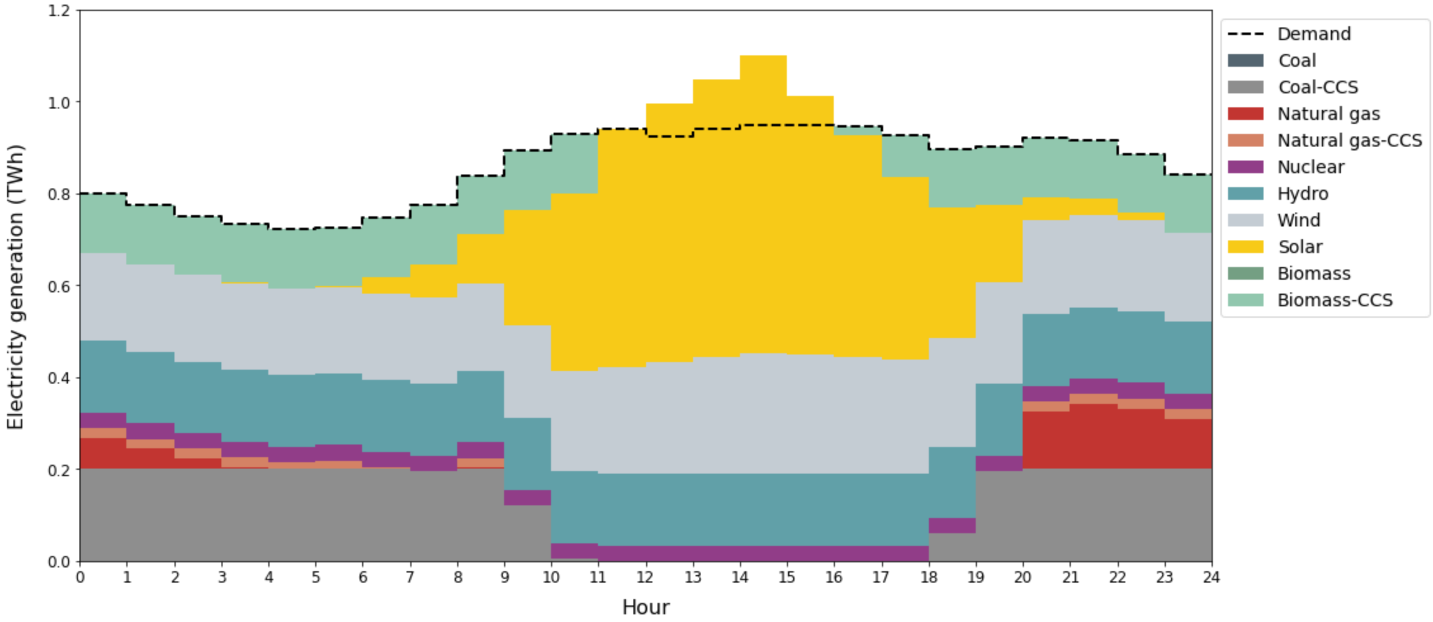

Fig. 2. Typical day power demand and supply profiles

is investigated with a case study on China's power sector in 2018. To achieve carbon neutral supply of electricity, the potentials of renewable resources are first collected from literature. Next, an optimization model is developed to minimize total annual cost subject to various operation and emission constraints. The results also provide quantitative estimate on the amount of power curtailment. Finally, the utilization potential of curtailed power to supply hydrogen as intermediates for chemical synthesis is studied. The formation of such nexus structure between energy and chemical sectors can significantly contribute to the decarbonization of methanol and ammonia production in China.

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