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Decarbonizing energy-intensive industries by coupling renewable energy and low-carbon technologies

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ABSTRACT

In 2020, China made an official announcement of reducing CO2 emissions and achieving carbon neutrality by 2060. Beyond the energy-related emissions, the steel and cement industries are typically fossil fuel-dependent and serve as the main contributors of CO2 emissions, which renders achieving carbon neutrality of particular challenges. These industries are highly energy-demanding, while only a few viable low-carbon solutions that would play a significant role during the transition from fossil fuels to renewable energies are commercially available. Herein, this study mainly focuses on the mitigation potential of low-carbon and carbon-negative technologies for these industries. An overall systematic optimizing model containing the above four industrial departments in China has been established, taking their regional demand, cost, GHG emissions, low-carbon strategies, etc. into consideration. According to the model, the most cost-effective solution supporting carbon neutrality by forming a combination of renewable energy, low-carbon and carbon-negative technologies, and energy-intensive sectors has been proposed and reasonably identified.

Keywords: carbon neutrality;
optimization;
energy;
chemical industry;
steel industry;
cement industry

NONMENCLATURE

Abbreviations	
GHG	Green-House Gas
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage

1. INTRODUCTION

The Paris Agreement had been approved by 178 countries at the end of 2015[1], which symbolized that the climate change, especially the increase of the concentration of GHG in the atmosphere, has become one of the most significant issues concerned worldwide. As for China, its annual CO_2 emissions have been increasing exponentially these years and has been up to 10 billion tons by 2018[2]. Responding to the current situation, the target of reaching “Carbon Peak” by 2030 and “Carbon Neutrality” by 2060, namely the Double Carbon Goal, was promoted in the General Debate of the seventy-fifth Session of the United Nations General Assembly[3].

Energy Industry is the foremost-emission department in China. It is surmised that 75% of GHG emissions comes from coal incineration, including some typical energy-intensive industries such as chemical industry, cement industry, steel industry and transportation department. Therefore, the deep decarburization in these sectors might be one of the effective guidelines for the Double Carbon Goal. The research of Yinan Li et.al. on "a quantitative roadmap for China towards carbon neutrality in 2060" using methanol and ammonia as energy carrier, promises an optimized combination of fossil fuels and renewable energy by forming "blue energy economy"[4], which is a systematic prediction and a reasonable guideline for the chemical sector and energy sector.

In this research, an overall optimizing model has been established containing the four typical energy-intensive industries above. Inheriting the results in chemical sector concluded by Yinan Li et.al., a more comprehensive and well-refined roadmap has been promoted based on this model.

2. METHODOLOGIES

As a preliminary explanation, the research framework is based on the input and output of energy and substances respectively for four major sectors: energy, chemical, cement and steel. In addition, we have considered the cross-coupling between the sectors. The framework might be clearly understood through **Figure 1**.

More detailed, we considered the technology parameters of each low-carbon technologies for each sector, containing its capacity, demand, cost, energy consumption, CO_2 emissions, potential and life time.

2.1 Energy sector

The energy sector can be regarded as the backbone of a county-wide industry. Dominated by electricity, it is inextricably linked to numerous energy-intensive industries, other than providing the daily energy expenses of roughly all inhabitants in a country. Zhang, X et.al. analyzed the share of consumption in the energy sector in China in 2018[5], with coal electricity alone accounting for about 1/3, while solar, wind and hydroelectricity in aggregation might count on approximately 1/3. Based on the current situation, we classified the energy types in China into traditional energy (coal and natural gas) and clean energy(solar, wind, hydro, biomass and nuclear). Moreover, CCS is adopted as a complement to low-carbon technologies.

2.2 Chemical industry

The chemical industry is one of the most energy-intensive industries. Among its energy consumption, which comprises mainly coal, electricity, natural gas and hydrogen, the largest portion comes from coal, accounting for about 21.1% in 2018[6] and bringing considerable CO_2 emissions. Considering the productions of methanol and ammonia are the major CO_2 emission process contributors in China, the technical parameters we investigated also mainly include the production process of these two chemicals. The technologies of these two industries are divided mainly by their ingredients, involving fossil ingredients as coal, coke-oven gas, natural gas and low-carbon ingredients as CO_2 and N_2.

2.3 Cement industry

The module of the cement industry consists of eleven energy-efficient technologies involving four major stages in the cement manufacturing[7]:

1. Fuel preparation:

(a)new efficient coal separators;

(b)efficient roller mills for coal grinding;

2. Raw materials preparation:

(c)variable frequency drives in raw mill vent fan;

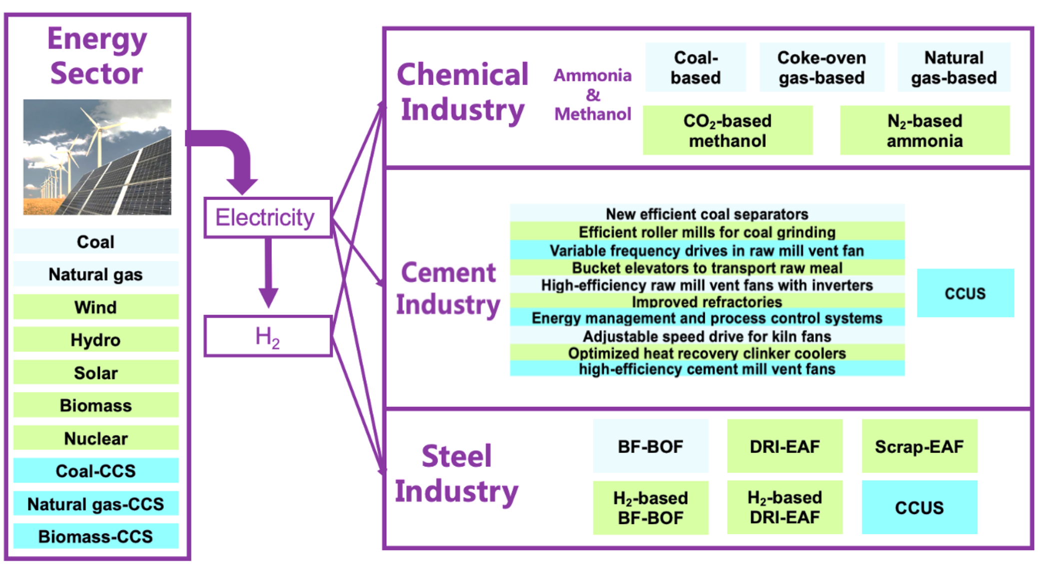

Fig. 1. The research framework covers four major sectors: energy, chemical, cement and steel. Energy efficiency improvement and low-carbon technologies are listed therein for each sector.

(d)bucket elevators to transport raw meal;

(e)high-efficiency raw mill vent fans with inverters;

3. Clinker making:

(f)improved refractories;

(g)energy management and process control system;

(h)adjustable speed drive for kiln fans;

(i)optimized heat recovery;

4. Finish grinding:

(j)high-efficiency cement mill vent fans.

Moreover, CCUS technology here is considered as a low-carbon technology.

2.4 Steel industry[8]

For steel industry, three basic technologies are considered:

(a) BF-BOF: blast furnace with basic oxygen furnace;

(b) DRI-EAF: direct reduced iron coupling with Electric Arc Furnace;

(c) Scrap-EAF: steel scrap utilization with Electric Arc Furnace.

Two hydrogen-energy coupling technologies;

(d) H_2-based BF-BOF;

(e) H_2-based DRI-EAF.

Moreover, plus CCUS technology in steel production process, which makes the module integral.

2.5 The optimization modeling

After preparing the aforesaid technical parameters for each sector, the following objective function (**Equation 1.**) is setup.

$$\min\ \text{Total Cost} = \sum_{i,j} \text{Capital Cost}_{t,i,j} \times x_{t,i,j} + \sum_{\substack{i,j \\ \tau \text{ in life time}}} \text{Fixed Cost}_{\tau,i,j} \times \left(x_{\tau,i,j} + C_{i,j}\right) + \sum_{i,j} \text{Variable Cost}_{\tau,i,j} \times y_{t,i,j} \qquad \text{(Equation 1.)}$$

Herein, by considering the capital, fixed and variable cost of each technology, an economically feasible carbon neutrality blueprint is envisioned for each energy-intensive sector with a minimum total cost.

Where t refers to the year (2018-2060), i refers to each province of China, j refers to each technology; x represents capacity expansion and y represents operation of technology, which are decision variables that measure the weighing of each technology; C is the technology capacity available before 2018.

The constraints are listed in **Table 1**.

Table 1. Constraints of the optimization model

Constraints
1. Lower bound constraint: The total capacity of each sector CANNOT be lower than the demand.
2. Upper bound constraints: (a) The technology capacity satisfies the maximum growth rate and maximum capacity limits. (b) The technology capacity satisfies the maximum capacity limit of the equipment.
3. Carbon Neutrality Target Constraint: Total emissions from all sectors meet the carbon neutrality target for 2060.

3. RESULTS DISCUSSION

For the energy sector (**Figure 2.**), though coal electricity with large emissions would remain dominant for a considerable period (2018-2040), it would be gradually replaced by clean energy with higher potential (e.g., wind and solar power) after 2030. CCS technologies for coal electricity would also reach a sizeable capacity after 2040.

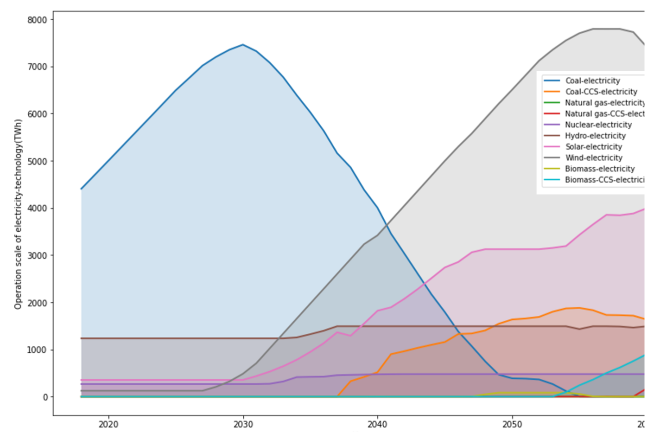

Fig. 2. Roadmap for energy sector.

For the chemical industry (**Figure 3.**), the production of methanol and ammonia are both undergoing a decarbonization tendency - coal to methanol and coal to ammonia are gradually replaced by low-carbon production technologies from large-capacity applications. Around 2055, CO_2 to methanol and N_2, electrolytic aquatic hydrogen to ammonia will respectively become the dominant technologies.

Diversity of technologies in the cement industry and the phenomenon of technology turnover are frequently observed in the optimized results (**Figure 4.**). In the fuel preparation stage, "new efficient coal

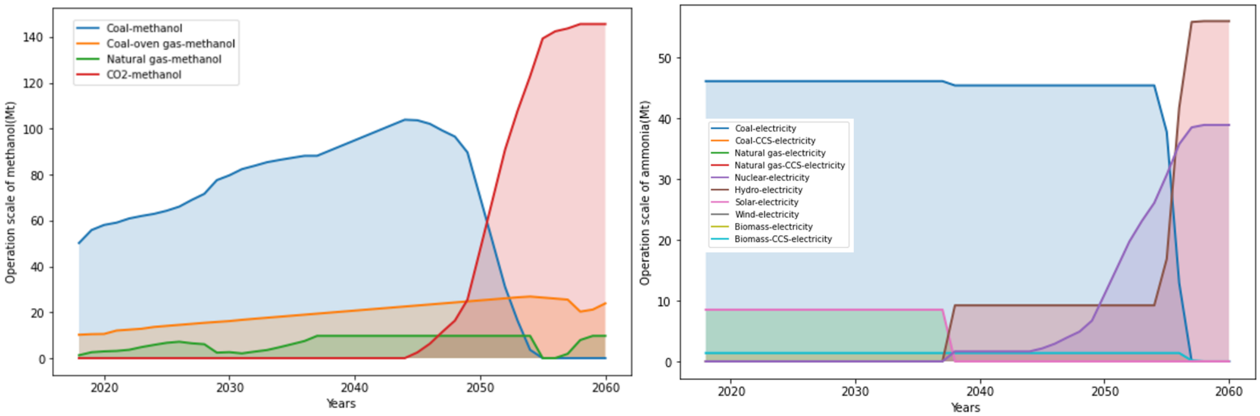

Fig. 3. Roadmap for ammonia industry.

separators" might dominate; in the raw materials preparation stage, "variable frequency drives in raw mill vent fan" gains the advantage; in the clinker making stage, the "optimized heat recovery" undergoes a two-stage rise. A relatively significant technology transition might also occur around 2048. According to the model, it is probably due to the greater dominance of more cost-efficient and emission-reduced technologies in the near-term of the carbon neutrality target. A conceivable explanation for the non-promotion of CCUS technology in the results is the high cost of current cement CCUS technology, preventing it from occupying a position in the optimization model. However, it is considered that the CCUS technology continues to hold high potential under the background of carbon neutrality.

4. CONCLUSIONS

In aggregate, a macroscopic carbon neutral roadmap is proposed in **Figure 5.**, which reveals the net GHG emissions of the above four energy-intensive sectors summed year by year. The carbon peaking in 2030 and carbon neutrality in 2060 could be plainly observed. All sectors demonstrate a trend towards

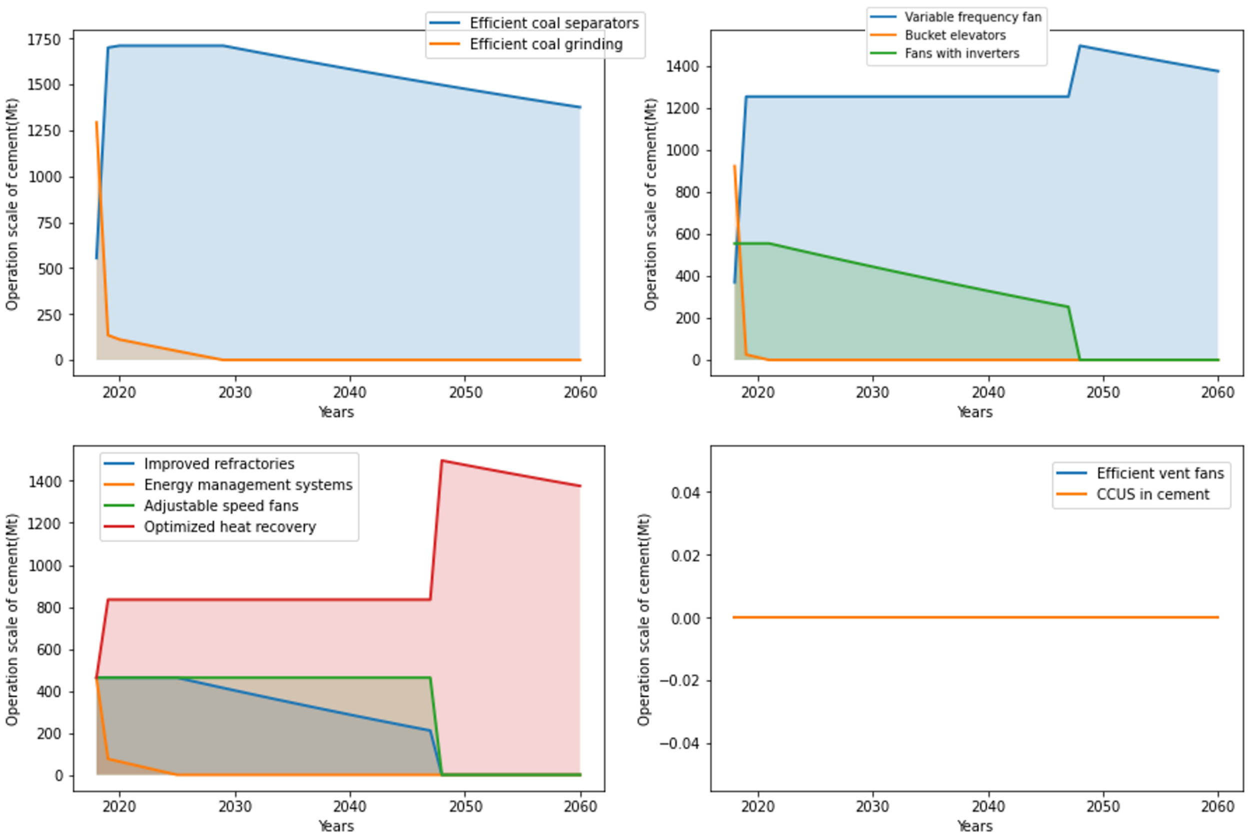

Fig. 4. Roadmap for cement industry.

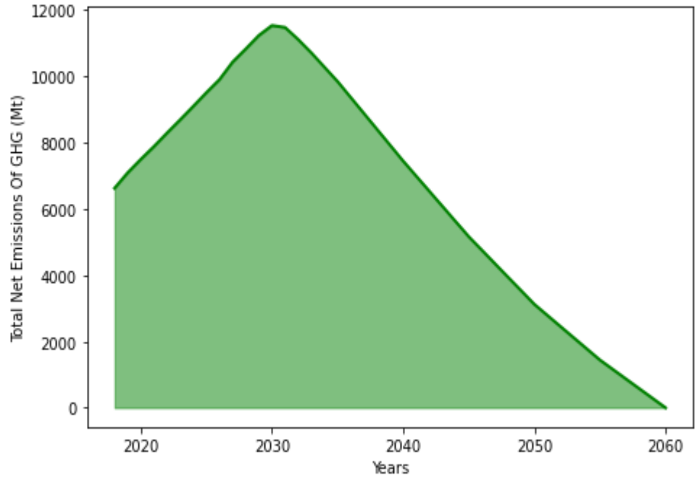

Fig. 5. The overall roadmap for carbon neutrality at the aspect of GHG emissions of the energy-intensive industries.

decarbonization, with clean energy gradually supplanting fossil energy. CCUS technologies also possess high potential as a catalyst for dual carbon goals.

Further research has to be conducted in the steel industry, where the partial parameters are insufficient for the optimization model and the complexity of this industry (the coupling of steel and hydrogen energy is still a significant factor to be evaluated). Furthermore, the optimization model requires further sophistication and refinement to ensure a more accurate prediction result.

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