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Achieving a low-carbon future through the inter-provincial energy-chemical-carbon markets in China

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ABSTRACT

In this study, inter-provincial energy, chemical and carbon markets are modeled for decentralized electricity, methanol and carbon permit trading among provinces in China under a cap-and-trade policy at province-level resolution. Optimization results reveal that China's national emission targets for electricity generation and methanol production can be achieved through carbon trading in the context of sectorial integration provided by energy-chemical nexus.

Keywords: energy-chemical nexus, cap-and-trade carbon scheme, decentralized optimization, market mechanism

NOMENCLATURE

Symbols	*Definitions/Remarks*
Sets:	
I	Set of provinces
K	Set of technologies
Decision variables (before decentralization):	
$X = (x_{i,k})_{i\in I,k\in K}$	Deployment of technology k in province i
$E = (e_{i,j})_{i,j\in I}$	Electricity transmission from province i to province j
$M = (m_{i,j})_{i,j\in I}$	Methanol transportation from province i to province j
$C = (c_{i,j})_{i,j\in I}$	Carbon permit sold by province i to province j
Local variables to province i (after decentralization):	
$X_i = (x_{i,k})_{k\in K}$ $E_i = (e_{i,j})_{j\in I}$ $E^i = (e_{j,i})_{j\in I}$ $M_i = (m_{i,j})_{j\in I}$ $M^i = (m_{j,i})_{j\in I}$ $C_i = (c_{i,j})_{j\in I}$ $C^i = (c_{j,i})_{j\in I}$	When local variables of one province are further indexed by other provinces, notations $(E_i)_j$ $(M_i)_j$ $(C_i)_j$ and $(E^j)_i$ $(M^j)_i$ $(C^j)_i$ are used in pseudocode to emphasize the scope of local variables.
Global variables (after decentralization):	
$\mathbb{E} = (\mathbb{e}_{i,j})_{i,j\in I}$	Global version of E
$\mathbb{M} = (\mathbb{m}_{i,j})_{i,j\in I}$	Global version of M
$\mathbb{C} = (\mathbb{c}_{i,j})_{i,j\in I}$	Global version of C
Others:	
$\lambda_{i,j}^{E},\ \mu_{i,j}^{E}$	Dual variables for electricity market
$\lambda_{i,j}^{M},\ \mu_{i,j}^{M}$	Dual variables for methanol market
$\lambda_{i,j}^{C},\ \mu_{i,j}^{C}$	Dual variables for carbon market
ρ	Penalty factor
γ^{pri}	Primal residue
ϵ^{pri}	Tolerance for primal residue
γ^{dual}	Dual residue
ϵ^{dual}	Tolerance for dual residue

1. INTRODUCTION

China has become the world's largest CO_2 emitter since 2006 and it is believed that the concept of energy-chemical nexus [1], which integrates the development of energy and chemical sectors to explore the potential inter-sectorial synergies between those two leading sectors in national carbon emission, can help the country to achieve a low-carbon future. For the concreteness of this work, electricity is selected as the representative product for energy sector as it currently constitutes more than 45% of China's total energy related CO_2 emission [2]. For chemical sector, methanol is selected considering its potential role as an energy carrier [3] and the fact that China has been the world's largest methanol producer and consumer since 2016 [4]. Finally, in order to regulate emission, a cap-and-trade policy is adopted in this work which sets a limit on total carbon emission first and distributes tradable carbon permits among emitters accordingly. For consistency, all carbon emissions are measured in $CO_{2\text{-eq}}$ for model parameters and results.

2. METHODOLOGY

In this work, the 31 provinces in China excluding Hong Kong, Macao and Taiwan are assumed to participate in inter-provincial energy-chemical-carbon markets where electricity, methanol and carbon permit can be traded among provinces. For each province, electricity can be generated from coal, coal with carbon capture and storage (coal-CCS), natural gas, natural gas-CCS, nuclear, hydro, wind, solar, biomass and biomass-CCS technologies while methanol can be produced from coal, coke-oven gas, natural gas and captured CO_2 with hydrogen supplied by water electrolysis.

The decentralized inter-provincial market model is formulated and solved via the Alternating Direction Method of Multipliers (ADMM) algorithm [5] as shown in Fig 1. In particular, for each province i, the cost function is given by

$$\mathrm{COST}(i) = \sum_k \beta_{i,k} x_{i,k} + \sum_j \alpha d_{j,i} m_{j,i}$$

where $\beta_{i,k}$ is the unit cost of technology k in province i, α is the cost of methanol transportation per distance in unit of [money·mass^{-1}·distance^{-1}] and $d_{j,i}$ measures the distance between province j and i.

The individual cost optimization at province level is subject to the following constraints. Firstly, both electricity and methanol demands must be satisfied.

$$\sum_k s_{i,k}^E x_{i,k} - \sum_j e_{i,j} + \sum_j \left(1 - \eta d_{j,i}\right) e_{j,i} \geq r_i^E$$

where $s_{i,k}^E$ is the electricity supplied by unit adoption of technology k in province i and it assumes a negative value if electricity is consumed by the technology, η measures the transmission loss rate in unit of [%·distance^{-1}] and r_i^E is the electricity demand of province i.

$$\sum_k s_{i,k}^M x_{i,k} - \sum_j m_{i,j} + \sum_j m_{j,i} \geq r_i^M$$

where $s_{i,k}^M$ is the methanol supplied by unit adoption of technology k in province i and r_i^M is the methanol demand of province i.

Also, from mass balance, the consumption of captured CO_2 and hydrogen must be supplied by relevant technologies.

$$\sum_k s_{i,k}^C x_{i,k} \geq 0 \quad \text{and} \quad \sum_k s_{i,k}^H x_{i,k} \geq 0$$

where $s_{i,k}^C$ and $s_{i,k}^H$ are the carbon captured and hydrogen supplied by unit adoption of technology k in province i, respectively. Their values will be negative for consumption.

Due to the intermittent natural of hydro, wind and solar power, their generation needs to be backed up before grid integration by conventional thermal generation from coal, natural gas and biomass with or without CCS [6]. However, if that intermittent electricity is consumed on the spot by water electrolysis to produce methanol from captured CO_2, no back-up is required.

while $\gamma^{\mathrm{pri}} > \epsilon^{\mathrm{pri}}$ **or** $\gamma^{\mathrm{dual}} > \epsilon^{\mathrm{dual}}$:

for each $i \in I$:

$$(X_i, E_i, E^i, M_i, M^i, C_i, C^i) = \operatorname{argmin} \mathrm{COST}(i) + \frac{\rho}{2} \sum_j \left(e_{i,j} - \mathbb{e}_{i,j} + \frac{\lambda_{i,j}^E}{\rho}\right)^2 + \left(e_{j,i} - \mathbb{e}_{j,i} + \frac{\mu_{j,i}^E}{\rho}\right)^2 + \left(m_{i,j} - \mathbb{m}_{i,j} + \frac{\lambda_{i,j}^M}{\rho}\right)^2 + \left(m_{j,i} - \mathbb{m}_{j,i} + \frac{\mu_{j,i}^M}{\rho}\right)^2 + \left(c_{i,j} - \mathbb{c}_{i,j} + \frac{\lambda_{i,j}^C}{\rho}\right)^2 + \left(c_{j,i} - \mathbb{c}_{j,i} + \frac{\mu_{j,i}^C}{\rho}\right)^2$$

subject to the cost function and constraints defined in Section 2.

update $\mathbb{e}_{i,j} = \frac{(E_i)_j + (E^j)_i}{2}$, $\mathbb{m}_{i,j} = \frac{(M_i)_j + (M^j)_i}{2}$ and $\mathbb{c}_{i,j} = \frac{(C_i)_j + (C^j)_i}{2}$

update $\lambda_{i,j}^E = \lambda_{i,j}^E + \rho\left((E_i)_j - \mathbb{e}_{i,j}\right)$, $\lambda_{i,j}^M = \lambda_{i,j}^M + \rho\left((M_i)_j - \mathbb{m}_{i,j}\right)$, $\lambda_{i,j}^C = \lambda_{i,j}^C + \rho\left((C_i)_j - \mathbb{c}_{i,j}\right)$ and
$\mu_{i,j}^E = \mu_{i,j}^E + \rho\left((E^j)_i - \mathbb{e}_{i,j}\right)$, $\mu_{i,j}^M = \mu_{i,j}^M + \rho\left((M^j)_i - \mathbb{m}_{i,j}\right)$, $\mu_{i,j}^C = \mu_{i,j}^C + \rho\left((C^j)_i - \mathbb{c}_{i,j}\right)$

compute $(\gamma^{\mathrm{pri}})^2 = \sum_{i,j} \left((E_i)_j - \mathbb{e}_{i,j}\right)^2 + \left((E^j)_i - \mathbb{e}_{i,j}\right)^2 + \left((M_i)_j - \mathbb{m}_{i,j}\right)^2 + \left((M^j)_i - \mathbb{m}_{i,j}\right)^2 + \left((C_i)_j - \mathbb{c}_{i,j}\right)^2 + \left((C^j)_i - \mathbb{c}_{i,j}\right)^2$

$\left(\frac{\gamma^{\mathrm{dual}}}{\rho}\right)^2 = 2 \sum_{i,j} \left(\mathbb{e}_{i,j} - \mathbb{e}'_{i,j}\right)^2 + \left(\mathbb{m}_{i,j} - \mathbb{m}'_{i,j}\right)^2 + \left(\mathbb{c}_{i,j} - \mathbb{c}'_{i,j}\right)^2$ where $\mathbb{e}'_{i,j}$, $\mathbb{m}'_{i,j}$ and $\mathbb{c}'_{i,j}$ denote variables in the previous iteration

Fig 1 Pseudocode for the market mechanism

$$\varepsilon\left(\sum_{k\in K_1} s_{i,k}^E x_{i,k} + \sum_{k\in K_2} s_{i,k}^E x_{i,k}\right) \le \sum_{k\in K_3} s_{i,k}^E x_{i,k}$$

where technology sets K_1 = {hydro, wind, solar power}, K_2 = {electrolysis, CO_2 hydrogenation}, K_3 = {coal, coal-CCS, natural gas, natural gas-CCS, biomass, biomass-CCS power} and ε is the electricity back-up rate for intermittent resources.

According to the cap-and-trade scheme, carbon emission should not exceed the permit after trading.

$$\sum_k f_{i,k} x_{i,k} + \sum_j f_{j,i} m_{j,i} \le p_i^E + p_i^M - \sum_j c_{i,j} + \sum_j c_{j,i}$$

where $f_{i,k}$ is the emission factor of technology k in province i and $f_{j,i}$ is that of methanol transportation from province j to i. p_i^E and p_i^M are the initial carbon permits of electricity and methanol sectors allocated to province i, respectively.

Finally, the adoption of all technologies should be within their respective capacities and all decision variables are non-negative by definition.

$$x_{i,k} \le u_{i,k} \quad \forall k$$

where $u_{i,k}$ represents the capacity of technology k in province i and

$$x_{i,k}, e_{i,j}, m_{i,j}, c_{i,j} \ge 0 \quad \forall k, j$$

3. RESULTS AND DISCUSSION

3.1 Results

The model parameters including projected cost and demand data to the year of 2050 are obtained from our previous work [7]. China's national carbon emission targets for electricity generation [8] and methanol production [9] in 2050 are estimated to be 806.4 and 236.3 Mt $CO_{2\text{-eq}}$, respectively, which are subsequently distributed to provinces as their initial carbon permits following a needs-based principle [10], i.e.

$$p_i^E = \frac{r_i^E}{\sum_j r_j^E} \cdot p^E \quad \text{and} \quad p_i^M = \frac{r_i^M}{\sum_j r_j^M} \cdot p^M$$

where p^E and p^M are national total carbon permits for electricity and methanol sectors, respectively.

Although the inter-provincial markets are fully peer-to-peer, the physical grid transmission of electricity and road transportation of methanol are assumed to happen only between adjacent provinces as shown in Fig 2. At markets equilibria, 78% of total electricity transmitted and 95% of total methanol transported across provinces are from intermittent resources (i.e. hydro, wind and solar) and CO_2 hydrogenation, respectively. Thus, to better illustrate the benefit of energy-chemical nexus, only intermittent electricity and green methanol are shown in Fig 2 with methanol converted to energy unit according to its heat value. The abbreviations of provinces are in accordance with [11].

With the formation of energy-chemical nexus, intermittent renewable resources can not only be

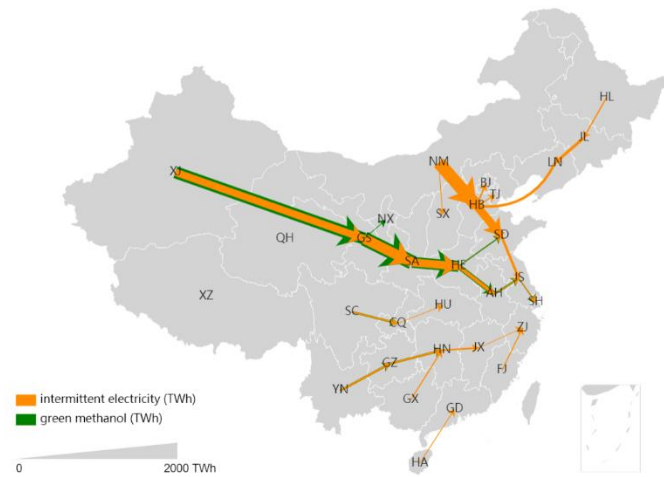

Fig 2 Intermittent electricity transmission and green methanol transportation

transmitted on power grid in energy sector, they can also be converted to green liquid methanol (i.e. methanol produced from renewable energy) and transported off grid in chemical sector. At markets equilibria, total grid transmission of intermittent electricity is 9736 TWh while total equivalent transmission via green methanol equals 2193 TWh, and methanol, as an alternative energy vector, effectively extends the transmission capacity of intermittent resources by 18%.

The initial and final distributions of carbon permits among provinces are shown in Fig 3. The initial allocations are proportional to local demands, thus provinces in Southeast China receive higher permits. However, due to the lack of renewable low carbon intensity energy sources, those provinces sell their permits to northwestern provinces in carbon market and buy electricity and methanol back in the energy and chemical markets. The average transaction price of carbon permits is 731.5 RMB/t $CO_{2\text{-eq}}$ in 2050, which is in agreement with the prediction of at least US$50–100/t CO_2 by 2030 [10] in order to achieve the Paris Agreement temperature target.

3.2 Future work

The inter-provincial markets model proposed in this work solves the energy-chemical nexus optimization problem under cap-and-trade carbon scheme at province-level resolution. The same framework can be modified to incorporate carbon tax scheme and will be

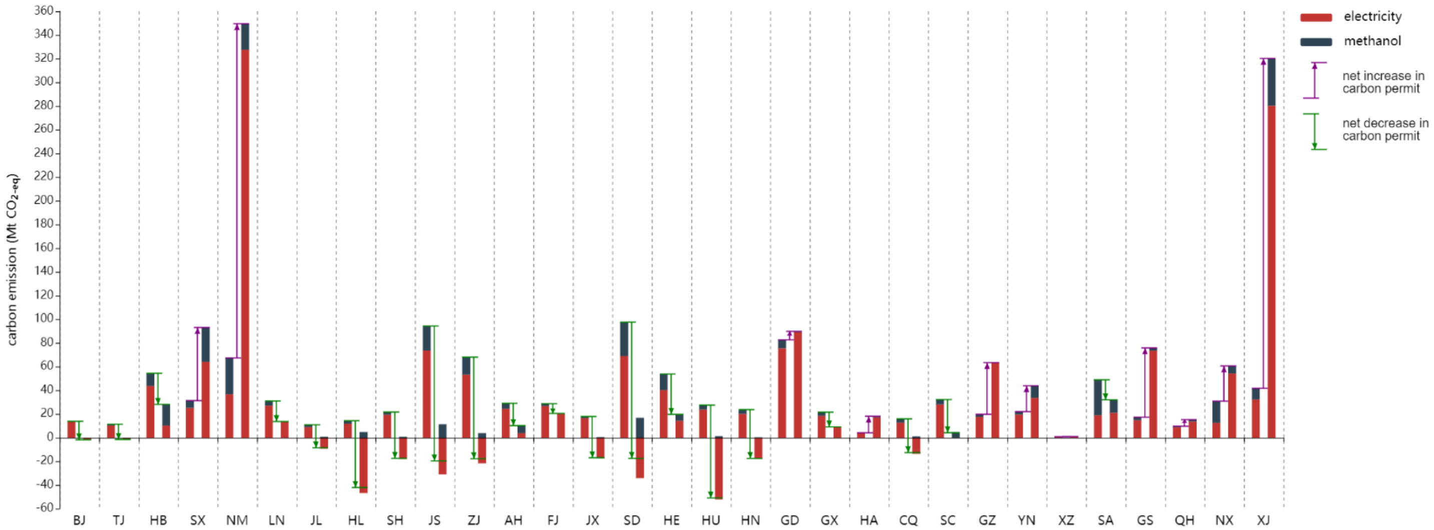

Fig 3 Initial (left) and final (right) distributions of carbon permits

applied to the study of inter-regional or international markets in the future.

Also, as a decentralized optimization algorithm, the market mechanism proposed in this work can be readily integrated with blockchain technologies [12], which will provide an additional layer of security, transparency and autonomy to the current framework.

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