Inter-regional power grid planning up to 2030 in China considering renewable energy development and regional pollutant control: A multi-region bottom-up optimization model

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Framework

1. Introduction
2. Methodology and scenarios design
3. Data
4. Results
5. Conclusions
1. Introduction

Background

- Electricity consumption from 2477.2 TWh in 2005 to 5523.3 TWh in 2014.
- Energy resources and electricity load show reverse regional distribution.
- China actively responds to current environmental and climate issues.
- Inter-regional power transmission play an important role in the power grid planning in the future, with the maturity of ultra high voltage (UHV) power transmission technology.
1. Introduction

Inter-regional power transmission capacity (GW) in 2015
1. Introduction

- Literature review

  - In China, the construction of inter-regional power transmission line and its relevant influence (Wang and Nakata, 2009; Zhou et al., 2010; Yang et al., 2016; Wang et al., 2014; Cao et al., 2016); but mainly focused on some particular areas or lines and seldom focused on the national inter-regional transmission planning.

  - Beyond China, the power sector planning in other countries by multi-region models (Abdollahi et al., 2016; Schaber et al., 2012; Chang and Li, 2013, 2015; Koltsaklis et al., 2014, 2015; Balash et al., 2013; Wang et al., 2015; Wright and Kanudia, 2014); but not suitable for China’s issue due to the significant differences of resource endowment and power grid structure between China and other countries.

  - Concerning China’s power optimization models, most studies simulate the power sector as a single region, without considering the heterogeneity between regions.
1. Introduction

Motivation

• What is the optimal evolution pathway of inter-regional power transmission line under various energy and environmental policy targets?
• What is the impact of inter-regional power transmission on China's power sector form the perspectives of renewable energy utilization, pollutant emissions, and coal consumption?

Pros

• Consider the investment, operation and maintenance, and substitution of different power transmission technologies over planning horizon.
• Simulate the flow of natural resources by adopting an inter-regional coal transportation sub-module into the conventional power generation expansion model.
2. Methodology and scenarios design

- An illustrative structure of the model

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Transmission technology
- Ultra high voltage direct current
- High voltage direct current

Power transmission Module

Local power demand

Power supply

Power generation Module

Power demand

Resource supply

Resource Module

Resource
- Coal, Natural gas, Uranium
- Water, Wind, Solar, Biomass

Coal import

Coal transportation Module

Coal export
2. Methodology and scenarios design

Technologies involved

<table>
<thead>
<tr>
<th>Power generation technology</th>
<th>Emission control technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercritical thermal power</td>
<td>Carbon capture and storage</td>
</tr>
<tr>
<td>Ultra supercritical thermal power</td>
<td>Flue-gas desulfurization</td>
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<tr>
<td>Integrated gasification combined cycle</td>
<td>Low NOₓ boiler</td>
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<tr>
<td>Other thermal power</td>
<td>Selective catalytic reduction</td>
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<tr>
<td>Gas-fired power</td>
<td></td>
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<tr>
<td>Hydro power</td>
<td></td>
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<tr>
<td>Wind power</td>
<td></td>
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<td>Nuclear power</td>
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<tr>
<td>Solar power</td>
<td></td>
</tr>
<tr>
<td>Biomass power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power transmission technology</td>
</tr>
<tr>
<td></td>
<td>Ultra high voltage direct current</td>
</tr>
<tr>
<td></td>
<td>High voltage direct current</td>
</tr>
</tbody>
</table>
2. Methodology and scenarios design

- **Methodology**
  - Minimize the accumulated overall cost of the China’s power sector.

\[
TPC = \sum_{t} \frac{TPC_t}{(1+ nir)^t} = \sum_{t} \frac{IC_t + OMC_t + EC_t + TIC_t + TOMC_t}{(1+ nir)^t}
\]

- The total costs:
  - The investment cost, O&M cost, fuel cost of power generation technologies.
  - The investment cost, O&M cost of power transmission technologies.

- Main constraints include:
  - Meeting each regions' power demand.
  - Carbon emissions constraint.
  - Renewable energy target constraint.
  - Technologies development speed and potential constraints.
2. Methodology and scenarios design

- **Scenarios**

  - **BAU scenario.** There is no mandatory policy target, indicating that the optimal pathways of power generation mix and power transmission lines are determined entirely from an economic view.

  - **FRO scenario.** The capacities of inter-regional power transmission lines remain at the level of 2015, and no new lines will be built in the future.

  - **POL scenario.** The SO\textsubscript{2} and NO\textsubscript{x} emissions in the North_Other, East_Other, and Central_Other regions during the planning horizon are assumed to reduce by 20\% respectively compared with the BAU scenario.

  - **REN scenario.** The policy target that the share of non-fossil fuels in primary energy consumption is about 20\% by 2030 is set up, referring to the “U.S.-China Joint Announcement on Climate Change”.
3. Data

- Data collected
  - The existing types of technologies, and the capacities and construction times for each of these technologies.
  - Parameters for power generation technologies.
  - Parameters for power transmission technologies.
  - Upper bounds for non-fossil energy capacities by 2030.
  - Regional upper bounds for annual operation hours of renewable energy.
  - Regional parameters of coal.
  - Coal transportation mode except direct railway transportation.
  - Power demand and peak load.
3. Data

- The existing types of technologies, and the capacities and construction times for each of these technologies.
3. Data

- Parameters for power generation technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment cost (RMB/kW)</th>
<th>O&amp;M cost (RMB/kWh)</th>
<th>Lifetime (year)</th>
<th>Energy consumption (kgce/kWh)</th>
<th>Learning rate</th>
<th>Initial rate of growth</th>
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<tbody>
<tr>
<td>Supercritical power</td>
<td>4050</td>
<td>0.059</td>
<td>30</td>
<td>0.293</td>
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<td>Ultra supercritical power</td>
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<td>IGCC</td>
<td>9970</td>
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<tr>
<td>Gas-fired power</td>
<td>2830</td>
<td>0.02</td>
<td>30</td>
<td>0.18⁹¹</td>
<td>0.13</td>
<td>0.08</td>
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<tr>
<td>Hydro power</td>
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<td>0.013</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
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<tr>
<td>Wind power</td>
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<td>20</td>
<td>0</td>
<td>0.13</td>
<td>0.06</td>
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<tr>
<td>Nuclear power</td>
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<td>0.107</td>
<td>60</td>
<td>0.0248⁹¹</td>
<td>0.1</td>
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<tr>
<td>Solar power</td>
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<td>20</td>
<td>0</td>
<td>0.18</td>
<td>0.09</td>
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<td>0.103</td>
<td>20</td>
<td>0.702</td>
<td>0.15</td>
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</table>

- Parameters for power transmission technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Fix investment cost (RMB/kW)</th>
<th>Variable investment cost (RMB/km/kW)</th>
<th>Lifetime (year)</th>
<th>Learning rate</th>
<th>Upper bound for annual transmission time (h)</th>
<th>Transmission loss (%/1000 km)</th>
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</thead>
<tbody>
<tr>
<td>Ultra high voltage direct current</td>
<td>1491</td>
<td>0.786</td>
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3. Data

- Upper bounds for non-fossil energy capacities by 2030

<table>
<thead>
<tr>
<th>Region</th>
<th>Hydro power (GW) (^{a})</th>
<th>Wind power (GW) (^{b})</th>
<th>Solar power (GW) (^{c})</th>
<th>Nuclear power (GW) (^{d})</th>
<th>Biomass power (GW) (^{e})</th>
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<td>Northeast_EIM</td>
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<td>72</td>
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<td>25</td>
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<td>North_Shannxi and WIM</td>
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<td>300</td>
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<td>60</td>
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<td>East_AnHui</td>
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<td>12</td>
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<td>12</td>
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<td>90</td>
<td>8</td>
<td>15</td>
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</table>

- Regional upper bounds for annual operation hours of renewable energy

<table>
<thead>
<tr>
<th>Region</th>
<th>Hydro power (h) (^{a})</th>
<th>Wind power (h) (^{b})</th>
<th>Solar power (h) (^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast_EIM</td>
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<td>2535</td>
<td>1562</td>
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<tr>
<td>Northeast_Other</td>
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<td>2119</td>
<td>1228</td>
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<td>North_Shannxi and WIM</td>
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<td>2418</td>
<td>1554</td>
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</table>
3. Data

- Regional parameters of coal

<table>
<thead>
<tr>
<th>Region</th>
<th>Price (RMB/t)</th>
<th>S content (%)</th>
<th>Heat value (kCal/kg)</th>
<th>Production proportion in 2014 (%)</th>
<th>Prediction of production proportion in 2030 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast_EIM</td>
<td>185</td>
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<td>3896</td>
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<td>Northeast_Other</td>
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<td>0.38</td>
<td>3896</td>
<td>3.2</td>
<td>1.1</td>
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<td>North_Shannxi and WIM</td>
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<td>0.91</td>
<td>4499</td>
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<td>51.9</td>
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<td>North_Other</td>
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<td>4499</td>
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<td>Northwest_Xinjiang</td>
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<td>5069</td>
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<td>5000</td>
<td>6.8</td>
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<tr>
<td>Foreign countries</td>
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</table>

- Coal transportation mode except direct railway

<table>
<thead>
<tr>
<th>Exporting region</th>
<th>Importing region</th>
<th>Transportation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast_Other</td>
<td>East_Other</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>Northeast_EIM</td>
<td>East_Other</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>North_Other</td>
<td>East_Other</td>
<td>Marine transportation</td>
</tr>
<tr>
<td>North_Shannxi and WIM</td>
<td>East_Other</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>North_Other</td>
<td>South_Other</td>
<td>Marine transportation to South_Guangdong + Railway transportation</td>
</tr>
<tr>
<td>Northeast_Other</td>
<td>South_Guangdong</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>Northeast_EIM</td>
<td>South_Guangdong</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>North_Other</td>
<td>South_Guangdong</td>
<td>Marine transportation</td>
</tr>
<tr>
<td>North_Shannxi and WIM</td>
<td>South_Guangdong</td>
<td>Railway transportation to North_Other + Marine transportation</td>
</tr>
<tr>
<td>East_Other</td>
<td>South_Guangdong</td>
<td>Marine transportation</td>
</tr>
</tbody>
</table>
### 3. Data

#### Power demand and peak load

<table>
<thead>
<tr>
<th>Region</th>
<th>Power demand in 2013&lt;sup&gt;a&lt;/sup&gt; (TWh)</th>
<th>Growth rate of power demand during 2014-2020 (%)</th>
<th>Growth rate of power demand during 2020-2030 (%)</th>
<th>Peak load in 2013 (GW)</th>
<th>Growth rate of peak load during 2014-2020 (%)</th>
<th>Growth rate of peak load during 2020-2030 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast_EIM</td>
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<td>4.9</td>
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<td>2.4</td>
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<td>2.7</td>
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<td>2.0</td>
<td>168.3</td>
<td>4.9</td>
<td>2.3</td>
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<td>2.2</td>
<td>77.3</td>
<td>5.0</td>
<td>2.3</td>
</tr>
</tbody>
</table>
4. Results

- **BAU scenario**

Newly built power transmission capacity (GW) during 2016-2030 in the BAU scenario
4. Results

- **BAU scenario**

  - UHV lines will become the main carrier of inter-regional power transmission. During 2016-2030, the newly built capacities of UHV lines reach 229.2 GW, while the high voltage lines are barely built.

  - East Inner Mongolia and Northwest regions gradually become the main power exporting regions, while Central, North, and East regions become the main power importing regions.
4. Results

- **FRO scenario**

Regional power installed capacity changes between BAU and FRO scenarios in 2030
4. Results

- FRO scenario

Accumulative air pollutant emissions changes between BAU and FRO scenarios during 2014-2030
4. Results

- FRO scenario

• From the economic perspective, the construction of transmission line between some regions such as from East Inner Mongolia to North, and from Northwest to Central, is more economical. BAU scenario reduces the total cost by 1.04% compared with FRO scenario.
• It will play an important role in promoting the development of renewable energy, especially for East Inner Mongolia and Northwest regions.
• However, the average efficiency of thermal power decreases slightly. The imported power substitutes a significant amount of new advanced coal-fired power generation capacities otherwise to be built in the East and Central regions.
• Inter-regional power transmission can effectively reduce the emissions of air pollutants in North, Guangdong, Central, and East regions, but have little effect on the national total emissions.
• It actually plays a positive role in alleviating above regions’ serious environmental issues. But the pollutant emissions have increased in East Inner Mongolia, Northwest, and Sichuan regions where remaining atmospheric environment capacity is larger.
4. Results

- POL and REN scenarios vs. BAU scenario

Net amount of power transmission in 2030 in each scenario
4. Results

- POL and REN scenarios vs. BAU scenario

  - For most of regions, power transmission is more widely under policy targets. The newly built transmission capacities during planning horizon reach 356.4 GW, and 304.2 GW, respectively, in the POL, and REN scenarios, which are much higher than that in BAU scenario. The specific type of transmission lines is UHV line, similar to BAU scenario.
4. Results

- **POL scenario**

   Newly built power transmission capacity (GW) during 2016-2030 in the POL scenario
4. Results

POL scenario

Accumulative air pollutant emissions changes between POL and BAU scenarios during 2014-2030.
4. Results

- **POL scenario**

  - To control the pollutant emissions in North, East, and Central regions, above three regions not only need to raise the proportion of clean energy, but also need to increase the electricity importing from other regions.
  - In 2030, the net imported power in North, East, and Central regions reach 696.0 TWh, 484.8 TWh, and 664.7 TWh, respectively.
  - The net exported power in Shanxi, West Inner Mongolia and Northwest regions increase a lot.
  - When there is more stringent regional emissions reduction policy, inter-regional power transmission will still play a role in controlling the emissions in central and eastern China.
  - The pollutant emissions in Shanxi, West Inner Mongolia, Northwest regions increase.
  - In addition to the cleaner power generation mix, transferring pollutant to regions where remaining atmospheric environment capacity is larger by power transmission is helpful for regional pollutant control.
4. Results

- **REN scenario**

Newly built power transmission capacity (GW) during 2016-2030 in the REN scenario.
4. Results

- REN scenario

Regional power installed capacity changes between REN and BAU scenarios in 2030

- Biomass power
- Solar power
- Nuclear power
- Wind power
- Hydro power
- Gas-fired power
- IGCC
- Ultra supercritical power
- Supercritical power
- Other thermal power
4. Results

- REN scenario

  - Xinjiang, Northwest, Shanxi, West Inner Mongolia, and Northeast regions need to develop renewable energy further to meet the target that non-fossil energy accounts for 20% in 2030.
  - The capacity of renewable energy increases a lot in Xinjiang province. In 2030, its net exported power reach 132.9 TWh, accounting for 30.9% of local power generation.
  - Another region where net exported power increases significantly is Shanxi and West Inner Mongolia. In 2030, its net exported power reach 501.1 TWh, accounting for 48.7% of local power generation.
  - We have found that inter-regional power transmission plays a strong role only in promoting the renewable energy development in East Inner Mongolia and Northwest regions from the economic view.
  - However, when renewable energy goal is considered into the model, inter-regional power transmission will also be an effective way to promote the utilization of renewable energy in Shanxi, West Inner Mongolia and Xinjiang regions.
5. Conclusions

Conclusion remarks

• The construction of transmission line between some regions rich in resources and regions with high demand can bring economic savings. These routes mainly include East Inner Mongolia to North China, Northwest to Central and East China.

• The optimal evolution pathways differ greatly under different policy targets. Except above-mentioned three main cost-effective routes, the routes from Shanxi and West Inner Mongolia to North, East, and Central are necessary under various policy targets set in this study.

• Inter-regional power transmission will play an important role in promoting the development of renewable energy, but may cause the average efficiency of thermal power decrease slightly.

• Inter-regional power transmission can effectively reduce the air pollutant emissions in densely populated, and heavily polluted eastern and central China, but have little effect on the national total emissions.

• Another significant effect of inter-regional power transmission is to reduce the coal transportation between regions, although it has limited effect on the total coal consumption in power sector.
Thanks for your attention.