Valuation of electricity transmission expansion under uncertainty: economic and environmental benefits

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INTRODUCTION

- Transmission Expansion has positive economic and environmental benefits:
  - Power prices.
  - GHG emissions.
  - Security of supply.
  - Competitiveness.
  - Less lost load.
  - ......

- But it has also negative environmental impacts on:
  - Land use.
  - Erosion risk.
  - Wildlife risk.
  - ......
OBJECTIVES OF THE MODEL TO BE DEVELOPED

• Valuation of transmission upgrades allowing for:
  ▪ Uncertainty.
  ▪ Market prices.
  ▪ Physical Characteristics.
  ▪ Operational Characteristics.
  ▪ At each time optimal operational model.

• Impact on consumers and power plants economics.

• Joint treatment of transmission and generation.

• Emphasis on CO₂ emissions and their economic value:
  ▪ Transmission grid upgrade and renewable energy penetration.
  ▪ Increased emissions under congestion.
  ▪ Transmission losses.
  ▪ Distributed generation.

• Network Topology
MODEL FEATURES (I)

- Stochastics Prices Models:
  - Coal
  - Natural Gas
  - Emission Allowances
  - Others

- Stochastic Outages:
  - Power Plants.
  - Transmission Lines.

- Operational Characteristics:
  - Power Plant Efficiency.
  - Transmission Losses.

- Financial Margins

- Stochastic Demand (with correlation).

Stochastic Supply Curve

Electricity Price

Stochastic Demand Curve
Model Features (II) Physical restrictions

Kirchhoff’s current and voltage laws
Stochastic Futures Prices: CO$_2$ Allowances on ETS

![Graph showing stochastic futures prices for CO$_2$ allowances on ETS. The graph includes price data from various dates, with price values ranging from 14.00 €/tonne to 26.00 €/tonne. The data is presented for different months, including Dec 13 to Dec 20, with trends indicating fluctuations in prices over time.](image-url)
Demand Probabilistic Model vs Demand Scenarios

![Graph showing demand scenarios over time](image)
Advantages of Probabilistic Model

- Valuation of risk.
- Loss-of-load probability.
- Consistent with quotes from futures markets.
- Market parameters estimation.
- Risk-neutral valuation (with risk premium).

Network Topology
### U.S. Transmission Losses (II)

#### Emissions per MWh in the US

<table>
<thead>
<tr>
<th>Year</th>
<th>Net Generation (Thousand MWh)</th>
<th>Emissions (Thousand Metric Tons)</th>
<th>Emissions per MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Carbon (CO₂)</td>
<td>Sulfur (SO₂)</td>
</tr>
<tr>
<td>1997</td>
<td>3,492,172.00</td>
<td>2,253,783.00</td>
<td>13,480.00</td>
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<tr>
<td>1998</td>
<td>3,620,295.00</td>
<td>2,345,951.00</td>
<td>13,464.00</td>
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<tr>
<td>1999</td>
<td>3,694,810.00</td>
<td>2,360,424.00</td>
<td>12,843.00</td>
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<tr>
<td>2000</td>
<td>3,802,105.00</td>
<td>2,464,550.00</td>
<td>11,963.00</td>
</tr>
<tr>
<td>2001</td>
<td>3,736,644.00</td>
<td>2,412,030.00</td>
<td>11,174.00</td>
</tr>
<tr>
<td>2002</td>
<td>3,858,452.00</td>
<td>2,417,327.00</td>
<td>10,881.00</td>
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<tr>
<td>2003</td>
<td>3,883,185.00</td>
<td>2,438,338.00</td>
<td>10,646.00</td>
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<tr>
<td>2004</td>
<td>3,970,555.00</td>
<td>2,479,971.00</td>
<td>10,309.00</td>
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<tr>
<td>2005</td>
<td>4,055,423.00</td>
<td>2,536,675.00</td>
<td>10,340.00</td>
</tr>
<tr>
<td>2006</td>
<td>4,064,702.00</td>
<td>2,481,829.00</td>
<td>9,524.00</td>
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<tr>
<td>2007</td>
<td>4,156,745.00</td>
<td>2,539,805.00</td>
<td>9,042.00</td>
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<tr>
<td>2008</td>
<td>4,119,388.00</td>
<td>2,477,213.00</td>
<td>7,830.00</td>
</tr>
<tr>
<td>Total</td>
<td>46,454,476.00</td>
<td>29,207,896.00</td>
<td>131,496.00</td>
</tr>
</tbody>
</table>

Source: made using EIA data (US Energy Information Administration).
### U.S. Transmission Losses (III)

<table>
<thead>
<tr>
<th>Year</th>
<th>Carbon (tonnes)</th>
<th>Sulfur Dioxide (tonnes)</th>
<th>Nitrogen Oxides (NO_x) (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>144,810,688</td>
<td>866,121</td>
<td>417,640</td>
</tr>
<tr>
<td>1998</td>
<td>143,244,278</td>
<td>822,115</td>
<td>394,388</td>
</tr>
<tr>
<td>1999</td>
<td>153,378,592</td>
<td>834,529</td>
<td>386,951</td>
</tr>
<tr>
<td>2000</td>
<td>157,845,466</td>
<td>766,187</td>
<td>361,093</td>
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<tr>
<td>2001</td>
<td>130,110,981</td>
<td>602,754</td>
<td>285,356</td>
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<tr>
<td>2002</td>
<td>155,237,741</td>
<td>698,764</td>
<td>333,552</td>
</tr>
<tr>
<td>2003</td>
<td>142,900,019</td>
<td>623,914</td>
<td>265,600</td>
</tr>
<tr>
<td>2004</td>
<td>166,089,861</td>
<td>690,420</td>
<td>277,467</td>
</tr>
<tr>
<td>2005</td>
<td>168,361,982</td>
<td>686,277</td>
<td>262,896</td>
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<tr>
<td>2006</td>
<td>162,583,624</td>
<td>623,913</td>
<td>248,871</td>
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<td>2007</td>
<td>161,417,961</td>
<td>574,667</td>
<td>231,977</td>
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<tr>
<td>2008</td>
<td>147,861,675</td>
<td>467,363</td>
<td>198,763</td>
</tr>
</tbody>
</table>
Prices on the wholesale electricity market

- The three possible designs:
  - Uniform pricing.
  - Zonal pricing.
  - Nodal pricing (Locational Marginal Price LMP).

- The congestion problem:
  - Insufficient transmission capacity.
  - Physics Laws.
  - Outages.

- Only under no congestion:
  - Uniform pricing = Zonal pricing = Nodal pricing.

- Δ Total Welfare
- Right signal for investment in generation and transmission.
- Operations of more expensive plants.
- More emissions.
- Decrease of Total Welfare
Initial demand at #1: 70 MWh

Initial demand at #2: 100 MWh
Economic benefits of transmission upgrade

1+2 = consumer's benefits of transmission upgrade

3+2 = economic benefits of transmission upgrade

Supply before transmission upgrade
Supply after transmission upgrade
Demand curve
Stochastic Optimal Control Problem
(Monte Carlo Simulation + Optimization)

- 1,000 simulations.
- Each simulation with 1,200 steps.
- 60 steps per year $\rightarrow$ 20 years.
- 1,200,000 Optimizations with:
  - Minimization:
    Production Cost (=Electricity Cost)+ Unserved Load Cost (VOLL)
  - Linear restrictions:
    Total Production=Supplied Power+Losses.
    $0 \leq \text{Production}_i \leq \text{Maximum Production}_i$
    \text{Supplied Power}_i \leq \text{Demanded Power}_i
  - Non-linear restrictions.

- Results: Production, Power Supplied, Total Costs, CO$_2$ Emissions, Financial cost of emissions; Upgrade Benefits.
GENERATION COSTS + VOLL

Mean L1 Model: $2,321.6 \times 10^6$

Mean L1+L2 Model: $1,930.2 \times 10^6$
CO$_2$ EMISSIONS (tonnes)

Mean L1 Model: $20,009 \times 10^3$

Mean L1+L2 Model: $20,252 \times 10^3$
FINANCIAL COST OF EMISSIONS

Mean L1 Model: $316.88 \times 10^6$

Mean L1+L2 Model: $319.1 \times 10^6$
## Basic Setup Summary

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>L1+L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost (million €) (*)</td>
<td>2321.2</td>
<td>1930.2</td>
</tr>
<tr>
<td>CO₂ emissions (million tonnes)</td>
<td>20.009</td>
<td>20.252</td>
</tr>
<tr>
<td>CO₂ emission cost (million €)</td>
<td>316.88</td>
<td>319.10</td>
</tr>
<tr>
<td>Generation (million MWh)</td>
<td>33.86</td>
<td>35.42</td>
</tr>
<tr>
<td>CO₂ emission (tonnes/MWh)</td>
<td>0.59</td>
<td>0.57</td>
</tr>
<tr>
<td>Load Lost (million MWh)</td>
<td>2.43</td>
<td>0.99</td>
</tr>
<tr>
<td>Transmission Lost (million MWh)</td>
<td>0.57</td>
<td>0.69</td>
</tr>
</tbody>
</table>

(*) Generation + Value of Lost Load
CONCLUSIONS

- Stochastic Optimal Control Model for valuation of transmission upgrades.
- Transmission and Generation are intimately interconnected.
- Transmission upgrades bring economic benefits for consumers.
- Transmission upgrades decrease the lost load and its cost (Value of Lost Load).
- CO2 emissions per MWh may decrease with transmission upgrades if these make possible an increased operation of cleaner power plants.
- CO2 emissions per MWh grow with transmission losses and may offset the benefits of using cleaner power plants when meeting the demand at other grid nodes.