Analysis of Carbon Taxation under Fuel Price Uncertainty in Japanese Energy System

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Energy situation in Japan

- Coal: the 1st largest importer (Korea², Taiwan³)
- Crude oil: the 2nd largest importer (USA¹, China³)
- Natural gas: the 3rd largest importer (USA¹, Germany²)
- Electricity production from fossil fuels:
  - Coal: USA¹, China², India³, ..., Japan⁵
  - Oil: Japan¹, USA², Saudi Arabia³
  - Natural gas: USA¹, Russia², Japan³, ..., Thailand⁷

This leaves the Japanese energy supply highly vulnerable to disruptions in the international energy markets.

Fuel price risk is then one of the most important uncertainties in the country’s energy security concerns.

Source: IEA (2006), Key world energy statistics.
Fuel price trends in Japan

Forecast: it is not easy!

Source: EDMC, 2004
Carbon taxation

- **The (basic) principle:** to increase prices according to the carbon content of different fuel sources
- **The aim:** to encourage the development and penetration of cleaner technologies, reducing CO₂ emissions
- **Policy dilemmas:**
  - A decision about carbon tax rate: should be a trade-off between controlling the level of CO₂ emissions and choosing clean technologies for investment allocation
  - Uncertainty in fuel prices: difficult to identify a least-cost/low-risk portfolio for the optimal allocation of investment (capacity expansion), and the range of plausible carbon tax rates that can mitigate fuel price risk
The aims

- Studies implications of fuel price uncertainty on the analysis of carbon taxation;
- Measures the fuel price risk and explores how it influences the decision-making process for the optimal allocation of investment (technology decisions);
- Provides a better understanding of how to design efficient planning/policy instruments (carbon tax rates) that impose the lowest risk;
- Improves ad hoc judgments required in traditional energy planning/policy decisions such as sensitivity, worst-case analyses.
Analysis techniques

Energy modeling and other analysis techniques to evaluate planning/policy under uncertainty have improved, but their implementation are uneven.

- Deterministic analysis
- Scenario analysis with focus on base-case forecast
- Scenario analysis with stochastic/probabilistic assessment
- Scenario analysis with multiple criteria decision-making

- Have not begun to regularly use sophisticated analysis techniques
- Optimizing for “least-cost” in deterministic framework, with limited scenario analysis
- Requiring ad hoc judgments for planning/policy decisions
- Increasingly using more sophisticated techniques to deal with uncertainty and multiple criteria/objectives
- Little work conducted so far on how fuel price uncertainty influence planning/policy decisions, benefits of RE in reducing fuel price risk, making trade-off

Adapted from Ryan H. Wiser (Lawrence Berkeley Lab.), 2004
A linear programming (LP) model incorporating Monte Carlo simulation (MCS) based on a bottom-up energy modeling structure

A hedging decision of capacity expansion (technology selection) under fuel price uncertainty

An objective function: to minimize expected total system costs (capital investment + O&M + fuel + associated with emission costs)

Subject to various constraints:
- system: energy balance, energy demands, system operation (existing and new), etc.
- user-given: technology profile, scenario analysis, etc.
Model framework

Technology characterizations
- investment, O&M, conversion efficiency, fuel consumption, lifetime, availability, emissions factor

Energy supply-demand
- existing capacity, end-use energy demand (e.g., electricity, heat and transportation), etc.

Optional port* (random generator)

*Other random distribution functions required the 3rd party random generator (e.g., excel, crystal ball, analytica)
Random fuel prices

- Randomness enters the model in the form of annual growth rates.
- The probability distribution function of these growth rates is assumed to be known.

\[ EP_{j,t+1} = EP_{j,t} \left(1 + GR_{j,t+1}^{random}\right) \]

<table>
<thead>
<tr>
<th>Fuel Types</th>
<th>Annual Growth Rateᵃ</th>
<th>Mean value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>+4.20%</td>
<td>30.35%</td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>+3.11%</td>
<td>27.59%</td>
<td></td>
</tr>
<tr>
<td>Fuel oil C</td>
<td>+1.19%</td>
<td>25.11%</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>+2.77%</td>
<td>23.47%</td>
<td></td>
</tr>
<tr>
<td>Fuel oil A</td>
<td>+3.37%</td>
<td>20.43%</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>+3.36%</td>
<td>19.43%</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>+4.88%</td>
<td>18.34%</td>
<td></td>
</tr>
<tr>
<td>Steam coal</td>
<td>-1.99%</td>
<td>16.86%</td>
<td></td>
</tr>
<tr>
<td>Coking coal</td>
<td>-2.91%</td>
<td>14.36%</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>+0.69%</td>
<td>9.23%</td>
<td></td>
</tr>
</tbody>
</table>

ᵃ Data calculated from 1975 to 2002 (EDMC, 2004).
ᵇ Calculated from import prices.
ᶜ Calculated from wholesale prices.
Objective function: minimize expected total system cost

Minimize
\[
\sum_{t=1}^{T} \frac{1}{(1+i)^t} \left[ \sum_{j=1}^{J} CI_{j,t} NEWCAP_{j,t}^{\text{cumulative}} \frac{i(1+i)^{l_j}}{(1+i)^{l_j} - 1} + \sum_{j=1}^{J} CF_{j,t} NEWCAP_{j,t}^{\text{cumulative}} + \sum_{j=1}^{J} EP_{j,t} FCONS_{j,t} NEWGEN_{j,t}^{\text{cumulative}} + TOTEMIS_{t,TAX} \right]
\]

Subjected to:

Capacity expansion, bound constraints
\[
NEW_{j,t}^{\text{cap}} \leq \text{bound}_{j,t}
\]
\[
NEWCAP_{j,t}^{\text{cumulative}} = \sum_{t=1}^{T} NEW_{j,t}^{\text{cap}}
\]
\[
TOTCAP_{j,t} = ESTCAP_{j,t} + NEWCAP_{j,t}^{\text{cumulative}}
\]

System operation constraints
\[
ESTGEN_{j,t} \leq AV_{j,t}^{\text{EST}} ESTCAP_{j,t}
\]
\[
NEW_{j,t}^{\text{gen}} = AV_{j,t}^{\text{NEW}} NEW_{j,t}^{\text{cap}}
\]
\[
NEWGEN_{j,t}^{\text{cumulative}} \leq \sum_{t=1}^{T} NEW_{j,t}^{\text{gen}}
\]
\[
TOTGEN_{j,t} \leq ESTGEN_{j,t} + NEWGEN_{j,t}^{\text{cumulative}}
\]

Investment decisions (technology selection)

Random fuel prices

Operating decisions
Mathematical formulation-2

- **Time construction constraints**

\[
\begin{align*}
AV_{j, t=1}^{NEW} &= AV_{j, t=2}^{NEW} = \ldots = AV_{j, t=5}^{NEW} = 0 & & \text{for a nuclear power plant} \\
AV_{j, t=1}^{NEW} &= AV_{j, t=2}^{NEW} = 0 & & \text{for conventional plants} \\
AV_{j, t=1}^{NEW} &= 0 & & \text{for renewable energy systems}
\end{align*}
\]

- **Energy supply-demand constraints**

\[
\begin{align*}
TRANSDEM_{k, t} (1 + \delta_k) &\leq \sum_{j \in \text{trans}(j)} TOTGEN_{j, t} \\
ELECDEM_{k, t} (1 + \delta_k) &\leq \sum_{j \in \text{elec}(j)} TOTGEN_{j, t} \\
HEATDEM_{k, t} (1 + \delta_k) &\leq \sum_{j \in \text{heat}(j)} TOTGEN_{j, t} + \sum_{j \in \text{CHP}(j)} TOTGEN_{j, t} HP_{j, k} \\
\sum_{j \in \text{trans}(j)} FCONS_{j, p, \text{TOTGEN}_{j, t}} &\leq \sum_{j \in \text{second}(j)} TOTGEN_{j, t}
\end{align*}
\]
Mathematical formulation-3

- **Electricity generation balancing constraints**

\[ PP_{k,t} = ELECDEM_{k,t} - SP_{k,t} \]

\[ SP_{k,t} \leq \sum_{j \in elec(j)} TOTGEN_{j,t}(1 - EX_{k,t}) \]

\[ LOSS \cdot PP_{k,t} \leq \sum_{j \in elec(j)} TOTGEN_{j,t} + SP_{k,t} \]

- **Renewable energy potential constraints**

\[ TOTGEN_{j \in re(j),t} \leq RP_{re(j),t} \]

- **Environmental constraints**

\[ TOTEMIS_t = \sum_{j=1}^{f} CO2EF_{j,t}FCONS_{j,t}TOTGEN_{j,t} \]
Case study

Future Scenarios

- Business as Usual (BAU)
- Carbon taxation (TAX): 100 US$/ton C, 350 US$/ton C

Assumed that revenues from taxation are not used to subsidize for energy programs

Model configurations (Japan)

- Energy-economic system: 55 energy conversion technologies, 15 end-use sectors
- Time frame: 2001-2025
- LP based: 9,004 constraints, 9,152 variables
- MC simulation: 2,000 samples, normal distribution
- Execution time: ~ 3-4 hours*

* Based on XP, 2.8 GHz, 2.0 GB RAM
Simulation results

- Decision-making of capacity expansion
  - Discussion is based on the expected (mean) value of Monte Carlo runs
  - Decision makers fairly hedge against the fuel price uncertainty, if they took this expected value as the decision
- Expected total system cost (objective function)
- Correlation of cost-risk-emissions
  - The risk was measured by the variance of Monte Carlo simulation
The decision is mostly made on coal technology, whereas renewable energy (wind power and biomass co-firing) share a small market penetration.
Carbon tax scenario

- For a “little less” control of CO₂ (100 US$/ton C), cumulative coal capacity is decreased by 7% compared to the BAU.

- For a “little more” control of CO₂ (350 US$/ton C), cumulative coal capacity can be reduced by 38% compared to the BAU. Those reduction are allocated to clean technologies.

- Among renewable, wind power can be viewed as the least-cost/low-risk option.
## Expected system cost

- **BAU scenario** imposes the lowest risk
- The higher carbon tax rate aimed to control the level of \( \text{CO}_2 \) emissions yields the higher risk
- **Does this behavior impose over a range of carbon tax?**

<table>
<thead>
<tr>
<th>Expected Total System Cost [US$ Billion]</th>
<th>Future Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU</td>
</tr>
<tr>
<td>Maximum value</td>
<td>172.923</td>
</tr>
<tr>
<td>Minimum value</td>
<td>159.522</td>
</tr>
<tr>
<td>Mean value</td>
<td>166.285</td>
</tr>
<tr>
<td>Variance</td>
<td><strong>4.802</strong></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.191</td>
</tr>
<tr>
<td>Probability within one STDV.</td>
<td>0.680</td>
</tr>
<tr>
<td>Probability within two STDVs.</td>
<td>0.959</td>
</tr>
</tbody>
</table>

‡‡ BAU scenario imposes the lowest risk
‡‡ The higher carbon tax rate aimed to control the level of \( \text{CO}_2 \) emissions yields the higher risk
‡‡ Does this behavior impose over a range of carbon tax?
Although the higher carbon tax rate can better reduce the CO₂ level, the fuel price uncertainty may yield the greater dispersion of expected CO₂ emissions.

The risk on the expected system cost does not vary proportionally to the carbon tax rates.
Key findings

- The risks both on the expected system cost and expected CO\textsubscript{2} emissions do not vary proportionally with the carbon tax rates;

- The diversifications of renewable energy and other clean technologies can mitigate these risks, if planning/policy instruments were properly designed (e.g., the carbon tax rate at 200 US$/ ton C imposes the lowest risk on the expected system cost);

- Wind power was found as one of the important parts of the least-cost/low-risk option among renewable energy.
Current limits

- It is difficult to estimate both the probabilities and the interrelations among random variables in MCS (e.g., correlation price of fossil fuels);
- Since values/benefits of renewable energy is hardly to quantify, making a cost-risk tradeoff without these values is somewhat unfair and unclear;
- Lacking of macroeconomic impacts; feedback effects of planning/policy on the economy cannot be discussed;
- Presentation of model outputs do not friendly provides decision makers with a clear picture of the implications for decision-making.
Conclusions

- This paper emphasizes the use of linear programming and Monte Carlo simulation to study the implications of fuel price uncertainty on the analysis of carbon taxation;

- The model offers an improved way over ad hoc judgments used in traditional analysis, and provide a better understanding in designing the plausible carbon tax rate that imposes the lowest risk;

- Fuel price uncertainty, willingness to pay for reducing fuel price risk, and benefit qualification of using renewable energy are priorities for energy-economic modeling work.
What we need?

- **Include** the recycle of tax revenues for subsidizing energy programs (e.g., the optimal rate of feed-in tariffs for renewable energy programs)

- **Modify** modeling work that can better address the tradeoffs among the cost, emission reduction, and risk of different technologies;

- **Develop** analysis tools to quantify other risks and benefits for the diversification of renewable energy and clean technologies;

- **Evaluate** the key instruments on planning/policy that can mitigate fuel price risks, including the range of plausible future price of fossil fuels and the value of information (willingness to pay) for price stability.
Thank You for Your Attention
Backup
What does the model do?

- Identifies the least-cost solution of resource use and technology deployment over time;
- Quantifies the sources of emissions from the associated energy system (now only CO$_2$);
- Quantifies the system effect of changes in resource supply, technology availability, and energy and environmental policies;
- Provides a framework for exploring and evaluating planning/policy, and the role of various technology.
MC simulation computes outcomes as functions of multiple uncertain inputs, each expressed as a probability distribution (e.g., normal function).

MC approach can allow for quantification and analysis of the differences between competing resource decisions and the relatively risks associated with each.
Model structure-1

- End-Use Energy
- Energy Demand
- Energy Supply

Emissions

Resource Allocation

Cost of Emissions Control

Numerical Input
- technology database
- structural activities
- resource limits
- efficiency potential

Command and Control
- static/dynamic
- simulation/optimization
- technological choice
- fuel choice
- technology description
- policy instrument
- activity description

Energy Modeling

Policy Design

Source: IEA (1998), Mapping the energy future: energy modeling and climate change policy.
Model structure-2

**Emissions**

- **End-Use Energy**
- **Energy Demand**
- **Energy Technology A**
  - investment cost
  - operating cost
  - efficiency
  - emission, etc.
- **Energy Technology B**
  - ...
  - ...
  - ...
  - ...
- **Energy Technology ...**

**Resource Allocation**

- **Energy Supply**
- **Economic Activity**
  - sub-sector A
- **Economic Activity**
  - ...

**Bottom-up perspective**

**IEA: International Energy Agency**
- Energy balances of OEDC countries
- Renewable information

**The Institute of Energy Economics (Japan)**
- Annual handbooks of energy & economic statistics

**NREL: National Renewable Energy Laboratory**

**EIA: Energy Information Administration**

**ECN: Energy Research Center of The Netherlands**

**IPCC: The Intergovernmental Panel on Climate Change**
- (for emission factors)

**Journal publications, etc.**
Flexible frameworks (optimization & simulation):

- **Deterministic-version:** long-term (technology & scenario) analysis, for model test run
- **Stochastic-version:** near-term analysis (5 yrs) with stochastic programming, various uncertainties, value of information
- **Boundaries:** country, region, multi-regions (target)

Flexible structures (incompleted):

- **Transparent module (load/edit/save/update):** various technology boxes, open model assumptions e.g., parameter setting, scenario, tech. profile, etc.
- **GUI:** User-friendly interface
Modeling dilemmas

- No model is ever finished (if it is, it’s not being used);
- No model can answer all questions (but it’s too expensive to build a model for each question);
- Exogenous is quite simple, while endogenous is much complicated and challenging;
- Insightful model results are easy to dismiss;
- Transparent models can’t do much;
- Economics are difficult, whereas social factors are incredible;
- Zero (and/or assuming constant) is the wrong input.

Adapted from Walter Short (NREL), 2001
The decision of capacity expansion is possibly switched to other technologies,

The decision (amount of capacity) itself exposes to the fuel price risk.

Under the low carbon tax rate, the decision of coal expansion is somewhat certain, except for the early of planning period that it would be possibly influenced by clean technologies (nuclear and wind).

The decision of coal expansion under the high carbon tax rate is more sensitive to fuel price uncertainty.
STDV. of natural gas and oil

- **Natural gas**
  
  - Under carbon tax, the decision is highly uncertain at the early and near the end of planning period.
  
  - Under 6% reduction target, the decision is certainly made on clean technologies, resulting the greater of STDV. as the volatile of gas price.

- **Oil**
  
  - The decision is rarely made and if it is required, it is avoided to invest with a large capacity at the early of planning period because of its highest of fuel price.
In 2001, 23% of total CO$_2$ emissions (~ 76 Million ton C) come from transportation sector.

- LPG combustion vehicles are a promising option since its fuel price is much cheaper than other petroleum products.

- To achieve reduction target, battery electric vehicle is noticeably required, but this decision is highly uncertain because of the replacement of existing gasoline vehicle and the gas price risk in the power sector.
Under the BAU, expected CO\textsubscript{2} emissions increases 36% over the 2001 level.

A “little less” control of CO\textsubscript{2} emissions (100 $/ton C) can mitigate the emission level by 3% compared to the BAU.

Expected CO\textsubscript{2} emissions for a “little more” control (350 $/ton C) is around 17% lower than the BAU scenario.

For 6% reduction target, it is difficult to achieve for the 1\textsuperscript{st} period of Kyoto (2008-2012) because of the limitations of clean technologies.
In general, the decision of carbon tax rate should be traded off between the control of CO₂ emissions and the investment cost of clean technologies.

- The risk of the expected system cost does not vary proportionally to the carbon tax rates.

- Although the higher carbon tax rate can better reduce the CO₂ level, the fuel price uncertainty may yield the greater dispersion of expected CO₂ emissions.