Technology Uncertainty and Climate Stabilization

What Can We Learn from a Large Set of Technology Scenarios?

GTSP
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Contributors

- Haewon McJeon*
- Leon Clarke
- Page Kyle
- Ben Bond-Lamberty
- Pralit Patel
- Marshall Wise
- Jae Edmonds
- Robert Lempert
- Andrew Hackbarth
- Ben Bryant

* hmcjeon@pnl.gov
Overview of the Project

- Developing large number of technology combination scenarios
- Assessing the impact of technology development on the range of stabilization cost (PNNL)
- Identifying technology combinations crucial in determining high-cost outcomes (RAND)
- Note that I will be switching back and forth between:
  - the pilot dataset based on 768 runs
  - the latest dataset based on 161,280 runs
How can we better inform R&D strategy:
(1) how much effort is appropriate?
(2) how should it be allocated?
Building upon Two Climate Change Integrated Assessment Modeling Research Traditions

1. Large Scale IAM Exercises
### Table 2. Assumed Correlations

<table>
<thead>
<tr>
<th>Variables</th>
<th>Parameter</th>
<th>Correlation</th>
<th>Explanation</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/GNP feedback elasticity OECD, non-OECD, Middle East</td>
<td>5.4</td>
<td>0.8</td>
<td>Regional E/GNP feedback elasticity</td>
<td>Similar transmission mechanisms, but magnitude of response is uncertain.</td>
</tr>
<tr>
<td>Income Elasticity: OECD, USSR, and LDCs</td>
<td>7.8</td>
<td>0.9</td>
<td>Regional income elasticities</td>
<td>Similar transmission mechanism. Middle East may be less similar due to dominance of oil production in the economy.</td>
</tr>
<tr>
<td>Labor Productivity: LDC's, DC's</td>
<td>31.32</td>
<td>0.9</td>
<td>Regional productivity</td>
<td>Engine of growth hypothesis, growth linked via capital, knowledge flows.</td>
</tr>
<tr>
<td>Exogenous energy efficiency, labor productivity in developed region</td>
<td>12.31</td>
<td>0.9</td>
<td>Labor and energy productivity</td>
<td>Increase in basic knowledge is the driving force and affects all factors equally.</td>
</tr>
<tr>
<td>Labor productivity in developed regions, with technological change in coal supply, technological change in shale oil supply, and technological change in nuclear power</td>
<td>31.60</td>
<td>0.6</td>
<td>Labor productivity and technological change in energy production</td>
<td>Increase in basic knowledge is the driving force and affects labor productivity and energy production technologies similarly.</td>
</tr>
<tr>
<td>Labor productivity, with environmental cost of shale oil production and environmental costs</td>
<td>31.69</td>
<td>0.9</td>
<td>Labor productivity and environmental costs</td>
<td>Higher income capita implies higher demands for clean environment.</td>
</tr>
</tbody>
</table>

Figure 1. Plot of carbon emission percentiles based on 400 runs.
Modeling Uncertainty of Induced Technological Change: (Gritsevskyi and Nakicenovic 2000)

Fig. 1. Global carbon dioxide emissions range for the full set of 130,000 scenarios with endogenous technological change comprising some 520 different technology dynamics against the range of more than 13,000 “optimal” scenarios from 53 different technology dynamics. All scenarios share a given useful energy trajectory, emissions range in GtC.

Fig. 2. Global carbon dioxide emissions for the range of some 400 scenarios from the literature, emissions range in GtC (Morita and Lee, 1998; Nakicenovic et al., 1998b).
Uncertainty in Greenhouse Emissions and Costs of Atmospheric Stabilization (Webster et al. 2008)

Figure 13. Probability density functions of global economic losses due to emissions reductions, measured as % change in consumption for the years (a) 2020, (b) 2060, and (c) 2100. The numbers indicate the values given as EPPA results in Clarke et al. (2007).

Figure 15. Uncertainty in global primary energy consumption by fuel in 2050. Each box indicates the 50% probability interval, the line inside the box indicates the median, and the whiskers indicate the 95% probability interval. Ranges are shown for energy consumption under No Policy (REF) and under the CCSP Level 2 (550ppm CO2) policy case.
Building upon Two Climate Change Integrated Assessment Modeling Research Traditions

2. Deep Dive: Focusing on Technology Interactions
## Building upon Representative Scenarios from the Climate Change Technology Program (CCTP)

<table>
<thead>
<tr>
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<tr>
<td>Transportation: Electric Vehicles</td>
<td>Reference</td>
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<td>Transportation: Other</td>
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<td>Reference</td>
<td>Advanced</td>
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<tr>
<td>Electricity and Hydrogen CCS</td>
<td>No CCS</td>
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<td>No CCS</td>
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<td>Agricultural Productivity</td>
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</tbody>
</table>
Technologies Affect the Cost of CO$_2$ Stabilization in a Non-Linear Non-Modular Way
## Exploring All Possible Combinations of CCTP Technology Modules for Deeper Insights of the Space

<table>
<thead>
<tr>
<th>Supply Technology</th>
<th>0: FIXED</th>
<th>1: REF</th>
<th>2: ADV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>N/A</td>
<td>Capital costs drop by 1%-2% per year 2005-2050</td>
<td>Capital costs drop by 2%-3.5% per year 2005-2050</td>
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<tr>
<td>Wind</td>
<td>N/A</td>
<td>Capital costs drop by 0.25% per year 2005-2050</td>
<td>Capital costs drop by 0.5% per year 2005-2050</td>
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<tr>
<td>CCS</td>
<td>No CCS in any applications</td>
<td>CCS available in electricity, hydrogen, and cement sectors (starting at about $40 / t CO2)</td>
<td>N/A</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Nuclear power generation fixed at 2005 levels</td>
<td>Nuclear power available at $2300/kW in 2020, decreasing at 0.1% per year</td>
<td>Nuclear power available at $2300/kW in 2020, decreasing at 0.3% per year</td>
</tr>
<tr>
<td>Buildings</td>
<td>N/A</td>
<td>Improvement in building technologies and shells based on EIA (2007)</td>
<td>Accelerated improvement in costs and performance of energy-saving technologies and building shells</td>
</tr>
<tr>
<td>Transport</td>
<td>N/A</td>
<td>Improvement in transportation technologies based on EIA (2007)</td>
<td>Accelerated improvements in conventional technologies, and availability of low-cost electric and fuel-cell light duty vehicles</td>
</tr>
<tr>
<td>Industry</td>
<td>N/A</td>
<td>Technology efficiencies improve at 0.1% per year; process intensities improve at 0.35% per year</td>
<td>Boiler and motor system efficiencies improve by 10% and 25% by 2035; best available practices from IEA (2007) are in use by 2035</td>
</tr>
<tr>
<td>Other</td>
<td>N/A</td>
<td>Long-term agricultural productivity improvement: 0.25% per year. Engineered geothermal systems (EGS) not available.</td>
<td>Long-term agricultural productivity: 0.5% per year. Accelerated improvements in hydrogen production. EGS available</td>
</tr>
</tbody>
</table>

Total combinations: $2^7 \cdot 3 = 384$ tech combinations per stabilization level
Total combinations with delays: $3^2 \cdot 4^4 \cdot 5 \cdot 7 = 80640$ combinations per level
Two Stabilization Levels Considered

- **History**
- **Projection**

- 550 ppm
- 450 ppm
Reading of the Model Output
Revealing the Interior of the Technology Space: a Plot of 768 Cases

The CCTP scenarios focused on the most critical combinations

Energy Consumption

2005-2095 Cumulative Primary Energy Consumption (Thousand EJ of Fossil Energy Equivalent)

Cost

2005-2095 NPV of Stabilization Cost (2005 Constant Trillions of Dollars)
Stabilization Cost Distribution Associated with Each Technology Type

- **No CCS**
- **Yes CCS**

- Stabilization Cost (2005 constant trillions of dollars)
- Frequency

**Graph Details:**
- X-axis: 2005-2095 Cumulative Primary Energy Consumption (Thousand EJ of Fossil Energy Equivalent)
Latest Additions: the Galaxy of 161k Technology Combinations
Carbon Capture and Storage (CCS)

Stabilization Cost (2005 constant trillions of dollars)

Frequency

F0: No CCS
Having CCS Compresses the Distribution

The availability of CCS truncates the upper tail – CCS provides a hedge against higher abatement costs.

Frequency

Stabilization Cost (2005 constant trillions of dollars)
Smaller Additional Compression from Cost Reduction

Frequency

Stabilization Cost (2005 constant trillions of dollars)

- F0: No CCS
- L0: High Cost CCS
- R0: Low Cost CCS
Early Availability of Low Cost CCS Induces Small but Noticeable Additional Compression
Early Availability of High Cost CCS Induces Much Smaller Additional Compression

High Cost CCS is not widely used as a competitive abatement option under less stringent constraint in early periods.

Only in the later periods when the constraint is stringent enough, does High Cost CCS becomes a viable option.
The Availability of CCS is More than Half the Story; Delays and Cost Reductions Explain the Remainder.
How Technologies Differ in their Influences on the Stabilization Cost Range
How Technology Influences the Stabilization Cost: (A) Compression of the Distribution

Unconstraining Nuclear truncates the upper tail – a hedging strategy against higher abatement costs.
How Technology Influences the Stabilization Cost: (B) Shifting of the Distribution

Advanced End-Use Technologies induce relatively constant shift – providing consistent benefit even under relaxed conditions.
How do We Use this Dataset to Inform Policy Making?
Policy Insights from the Dataset: (A) Inter-Technology Comparison

Stabilization Cost (2005 constant trillions of dollars)
Frequency
BLD-1: REF
BLD-2: ADV

Policy Insights from the Dataset:
(A) Inter-Technology Comparison

Lower 1/4
Middle 1/2
Upper 1/4

min
max
(A1) Which Technologies Guarantee Limiting Stabilization Cost under $10 tril?
(A2) Which Criterion is the Most Crucial?
(B) “Value of Technology”: Stabilization Cost Reduction Potential

![Graph showing stabilization cost reduction potential across different technologies]

- Stable cost reduction potential across various technologies.
- CCS (Carbon Capture and Storage) and other technologies depicted.
- 2005 constant billions of dollars and trillions of dollars.
Here, “Value of Technology” is defined as:

The difference in the net present value of total stabilization cost

Between Scenarios with and without the technology in concern;

Holding all other technologies equal;

With 768 runs, we have 384 data points of Value of Technology per binary technology options, and 256 for trinary (nuclear).

The charts show the “Bang” in the Bang-for-Buck approach.
(B1) Compression vs. Shift

Long-tail: Large range of possible value from simply having one additional supply technology. Particularly valuable if no other advanced technologies are available.

Compact-body: End use technologies provide a relatively consistent value.

Near-zero VT: Smaller value from incremental improvements in performance. Value is already captured in the reference technology.

450 ppm

2005 constant billions of dollars

CCS
TRANSPORT
NUCLEAR-A
BUILDING
INDUSTRY
SOLAR
NUCLEAR-B
WIND

* From “No New Nuclear” to REF Nuclear
** From REF Nuclear to ADV Nuclear

33
(B2) Changes in Relative Performance with respect to Stabilization Target

* From “No New Nuclear” to REF Nuclear
** From REF Nuclear to ADV Nuclear
End-use technologies move up in rankings in 550 ppm level:
- End-use techs provide relatively consistent value regardless of stabilization level

Value of nuclear power exceeding value of CCS in 550 ppm level:
- Limited low-cost tech has relatively high value in less stringent case
- Abundant high-cost tech has relatively high value in stringent case
PARAMETER RESTRICTIONS

<table>
<thead>
<tr>
<th>Box ID</th>
<th>BUILDING</th>
<th>TRANSPORT</th>
<th>CCS</th>
<th>Density</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference</td>
<td>Reference</td>
<td>Fixed</td>
<td>0.6458</td>
<td>0.8052</td>
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<tr>
<td>2</td>
<td>Reference</td>
<td>Reference</td>
<td>Fixed</td>
<td>0.9375</td>
<td>0.5844</td>
</tr>
<tr>
<td>5</td>
<td>Reference</td>
<td>Reference</td>
<td>Fixed</td>
<td>0.4010</td>
<td>1</td>
</tr>
</tbody>
</table>

High Cost SoWs: 90% threshold, no-CCS

- **Building**
  - Total SoW
  - High Cost
- **Transport**
  - Reference
  - Advanced
Possible Directions for Future Work

- Uncertainty analysis: Integrating probabilities of success
  - R&D portfolio planning
  - Stochastic programming
  - Monte Carlo analysis

- Disaggregation of End-Use technologies
  - Battery electric vehicle vs. Gas-electric hybrid vehicle
  - Geothermal heat-pump vs. Efficient insulation

- Suboptimal Policy Regime
  - Delayed participation of developing countries
  - Limited technology diffusion
Thank You

Questions and Comments