Climate Targets under uncertainty

Analysis with The ETSAP-TIAM Model

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Acknowledgments

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  – Antti Lettila, VTT, Finland: GAMS code

• US EPA
  – F. Delachesnaye: data on other gases and on biological carbon sequestration

• IEA, ETP division
  – Dolf Gielen: input data on sequestration etc.

• NSERC (Research Council, Canada)
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I: OBJECTIVE

Assess the feasibility, cost, and means of maintaining average surface temperature increase within the 2 °C to 3°C range (long term), under high economic and climate uncertainty
II: METHODOLOGY
ETSAP-TIAM
( TIMES Integrated Assessment Model )

- Technology rich, integrated energy/emissions model
- Dynamic inter-temporal partial equilibrium (with variable-length periods)
  - Based on maximum total surplus (L.P.) with own-price elastic service demands
- Linked to a CGE model (GEM-E3 or GEMINI-E3) to obtain reference case socio-economic drivers for initial service demands
- 15 regions linked by ~10 commodity trades
- Horizon to 2100, salvage value at EOH
Schematics of TIAM Climate Module

Emissions

15 region

TIAM Model

CH4

CONCENT. ATM

N2O

CONCENT. ATM

CO2

CONCENT. ATM

CONCENT. OCEAN UP

CONCENT. OCEAN LO

Exo Forc

CH4 Forc

N2O Forc

CO2 Forc

Σ Forcings

DELTA T SURFACE

DELTA T DEEP

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Original Climate equations (adapted from Nordhaus and Boyer, 1999)

Concentrations of GHG’s

**CO₂ mass:** 3-layer model (Nordhaus and Boyer 1999)

- \( CO₂_{atm}(t) = Emi(t) + CO₂_{atm}(t-1)(1-f_{atm,up}) + CO₂_{up}(t-1)f_{up,atm} \)
- \( CO₂_{up}(t) = CO₂_{up}(t-1)(1-f_{up,atm} - f_{up,lo}) + CO₂_{lo}(t-1)f_{lo,up} + CO₂_{atm}(t-1)f_{atm,up} \)
- \( CO₂_{lo}(t) = CO₂_{lo}(t-1)(1-f_{lo,up}) + CO₂_{up}(t-1)f_{up,lo} \)

**CH₄ mass:** 1-box expon. decay model (Monni et al, 2003)

**N₂O mass:** 1-box expon. decay model (Monni et al, 2003)
Climate equations in TIAM

Radiative forcings (IPCC 2001, 2007)

\[ \Delta F_{\text{CO}_2}(t) = \gamma / \ln 2 \times \ln \left[ \text{CO}_2_{\text{atm}}(t) / \text{CO}_2_{\text{atm}}(\text{pre-ind}) \right] \]

\[ \Delta F_{\text{CH}_4}(t) = \]

\[ \Delta F_{\text{N}_2\text{O}}(t) = \]

with: \( f(x,y) = \)

\[ \Delta T_{\text{up}}(t) = \Delta T_{\text{up}}(t-1) + \sigma_1 \times \left\{ \Delta F(t) - 3.7/C_s \times \Delta T_{\text{up}}(t-1) - \sigma_2 \left[ \Delta T_{\text{up}}(t-1) - \Delta T_{\text{lo}}(t-1) \right] \right\} \]

\[ \Delta T_{\text{lo}}(t) = \Delta T_{\text{up}}(t-1) \times \sigma_3 + \Delta T_{\text{lo}}(t-1) \times g_{22} \]

(At equilibrium: \( \Delta F(t) = 3.7/C_s \times \Delta T_{\text{up}} \))
Linear approximations

• The 3 forcing equations are replaced by linear approximations within the intervals of interest, for instance: 375 ppm-550 ppm for CO2

• Each approximation is halfway between the chord and the tangent of the exact curve

• Within the selected range, the errors made on Forcings never exceed 2% (well within the inherent uncertainty of exogenous forcing values)
Approach taken

• Impose an upper bound on $\Delta T_{atm}(2100)$

• Run TIAM (stochastic LP in extensive form)
  – Uncertain Cs and Lag
  – Uncertain GDP growth rates (most TIAM demands are correlated to GDP)

• Observe climate variables (Concentrations, Forcing, Temperature $\Delta t_{atm}$)
  – Up to 2100: from TIAM results
  – Beyond 2100: from Excel simulation sheet
III. Scenarios
Uncertainties considered

Uncertainties treated explicitly via Stochastic Programming

– Climate sensitivity \( C_s \) and Lag parameter \( \sigma_1 \)
– Economic growth (and thus GHG emissions)

Other uncertainties, explored via andAlternate reference scenario
## Description of Uncertainties
**(as per EMF-22, 2005)**

<table>
<thead>
<tr>
<th></th>
<th>Economic Growth</th>
<th>Climate Sensitivity $C_s$</th>
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<tr>
<td><strong>Unknown until and including</strong></td>
<td>2040</td>
<td>2040</td>
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<tr>
<td><strong>First certainty period in TIAM</strong></td>
<td>2050</td>
<td>2050</td>
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<tr>
<td><strong>Values</strong></td>
<td>2 scenarios</td>
<td>4 possible values (1.5, 3, 5, 8 °C)</td>
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<td></td>
<td>High and Low</td>
<td>with Lag parameter adjusted accordingly</td>
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<td>(High growth ~ 2 x Low Growth)</td>
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<td><em>Equal likelihood 0.5</em></td>
<td><em>Discrete Probability Distribution</em></td>
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PDF of $C_s$
(from Schlesinger and Andropova, 2001; Yohe et al. 2004)

Cumulative Probability

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<tr>
<th>Climate Sensitivity Cs (°C)</th>
<th>Prob</th>
<th>Lag $\sigma_1^*$</th>
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<tbody>
<tr>
<td>1.5 °C</td>
<td>0.25</td>
<td>0.0657</td>
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<td>3 °C</td>
<td>0.45</td>
<td>0.0146</td>
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<td>5 °C</td>
<td>0.15</td>
<td>0.0103</td>
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<td>8 °C</td>
<td>0.15</td>
<td>0.0089</td>
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Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Event Tree
Uncertain climate only

TIMES periods

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
• If both $C_s$ and demands are uncertain

  – After 2040, GDP* growth is uncertain

    • LOW (2/3 of Base) with prob. 0.5
      $\text{GDP}_{2100} = 7\times\text{GDP}_{2000}$

    • HIGH (4/3 of Base) with prob. 0.5
      $\text{GDP}_{2100} = 12\times\text{GDP}_{2000}$

*Note: Most TIAM demands are strongly correlated to GDP

► HOWEVER: Results show that Stochastic demands do NOT require new hedging decisions that are different from those adopted under Stochastic Cs only scenario.

► No need to anticipate GDP growth
Is Hedging relevant?

Hedging is relevant if decisions prior to 2040 are different under hedging than under Base (which ignores climate issues)

Otherwise, ‘wait and see’ is a good policy

*Main interest of a hedging strategy = what to do prior to the resolution date*

Observation: Hedging is relevant for climate uncertainty but not for GDP growth uncertainty
Two Reference Scenarios

Case I. **Average Development** Base Case  
(somewhat close to IPCC SRES B2 scenario):

- World GDP 2100 = 8*GDP in 2000 (avg 2.3%/yr)
- Moderately high technical progress
- Large oil resources (by region)
- Large Biomass resources (by region)
- Moderately large Nuclear allowed (Region dependent)
Two Reference Scenarios Cont’d

Case II. **Fast Development** Base Case:

– World GDP 2100 ~ 14*GDP in 2000 (avg 2.9%/yr)
  
  • Higher technical progress in CGE model
– Larger Nuclear potentials (region dependent)
– Larger Hydro potentials (region dependent)
– Advanced vehicles (and fuels) available earlier
– Same oil resources (by region)
– Same Biomass resources (by region)
Eight temperature targets under two scenarios, climate uncertainty only

Under the Fast development scenario, reachable targets are shifted by ~ 0.7-0.9°C

Expected costs of various targets (B$ NPV)

<table>
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<tr>
<th>Delta T</th>
<th>1.5</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>2.25</th>
<th>2.5</th>
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<td>FAST</td>
<td>25200</td>
<td>9080</td>
<td>1692</td>
<td>250</td>
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NPV of world GDP ~ 950,000 B$ under STD and ~1,200,000 B$ under FAST
IV: RESULTS for 2 contrasted scenarios

- Explicit uncertainty on Cs only
  - FAST DEVT Scenario
    2.5°C target in year 2100
  - Average Devt Scenario
    1.8°C target in year 2100
### Expected Value of Information (EVI) for the Avg Devt. Scenario, target 1.8°C

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<tr>
<th>Resolution date</th>
<th>Expected Loss of surplus</th>
<th>Expected value of information</th>
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<tr>
<td>2040</td>
<td>1,692 B$</td>
<td>-</td>
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<tr>
<td>2005 (perfect info)</td>
<td>1,135 B$</td>
<td>EVPI = 557 B$</td>
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<td>2020 (earlier info)</td>
<td>1,230 B$</td>
<td>EVII = 462 B$</td>
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### for the Fast Devt. Scenario, target 2.5°C

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<th>Resolution date</th>
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<th>Expected value of information</th>
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<td>2040</td>
<td>10,340 B$</td>
<td>-</td>
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<tr>
<td>2005 (perfect info)</td>
<td>3,690 B$</td>
<td>EVPI = 6,650 B$</td>
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<tr>
<td>2020 (earlier info)</td>
<td>To Do</td>
<td>To Do</td>
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Short term evolution of temperature (Hedging, Fast devt, Target=2.5°C)

Target not binding
Short Term Temperature evolution
Hedging, Avg Devt, Target=1.8°C

Target not binding for Cs=1.5
Short term evolution of temperature
Hedging and Blind strategies, Target=2.5°C
GHG Emissions
Avg Devt, Target=1.8°C

GHG emissions for $\Delta T_{\text{limit}} (2100) = 1.8°C$
$\Delta T_{\text{max}}$ (long term) = 2.7°C

- BC = PF 1.5°C
- PF 3°C
- PF 5°C
- PF 8°C
- HEDGING 1.5°C
- HEDGING 3°C
- HEDGING 5°C
- HEDGING 8°C

Hedging strategies, R. Lou lou, EMF-22 Wash DC 2008
GHG Emissions
Fast Devt, Target=2.5°C

Planning for the worst Cs is a bad idea

Both Cs=1.5 and Cs=3

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Longer term Temperature

- Model horizon: 2100
- We need an emission profile beyond 2100
- Three alternative assumptions
  - A) Emissions decline to 0 over 100 years
  - B) Emissions decline to 0 over 200 years
  - C) Emissions decline to 0 at fixed rate (0.28 GtC/year)
Long term temperature evolution
Hedging, Target = 2.5 oC in 2100
assuming emissions after 2100 disappear in 2200

Cs=8 has a lower peak temperature than Cs=5 or 3!
Long term temperature evolution
Hedging, Target = 2.5 oC in 2100
assuming emissions after 2100 disappear in 2300

Cs=8 has a lower peak temperature than Cs=5 or 3!
Long term temperature evolution
Hedging, Target = 2.5°C in 2100
assuming emissions after 2100 decrease at rate 0.28 GtC/year

Cs=8 has a lower peak temperature than Cs=5 or 3!
GHG Price
Avg Devt, target = 1.8oC

- Hedging differs from all perfect forecast strategies
- Low price before 2040: CH₄ and forestry measures help!
- Long term high price: due to the absence of CH₄ abatement options in agriculture
GHG Price, Fast Devt
Targets = 2.5 and 2.25 oC

Planning for the worst Cs is a bad idea

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Main conclusions

• Long term Temp target achievable under Cs uncertainty at reasonable expected cost:
  – 2.7 °C in Avg Devt scenario
  – 3.5 °C in Fast Devt scenario, in spite of enhanced technical progress

• Hedging is important for Cs uncertainty, but not for economic uncertainty (tentative)

• High EVPI: incentive for research on Cs

• Stochastic programming produces a hedging strategy against climate uncertainty, that is not always well approximated by any PF strategy

• Hedging strategy not always well approximated by any deterministic strategy
To Do

• **Further analyses**
  – Detailed technological and regional analysis
  – Evaluate expected cost of *wait-and-see* strategy (i.e. follow Base until 2040, then optimize)

• **Model improvements**
  – Refine relationship Lag ↔ Cs
  – Enhance the model with feedbacks from Climate to Economy
    • Eg. modified demands for space heating and cooling, hydro potentials, release of methane from permafrost, land use changes,…
Complements: additional results for the Avg Devt Scenario
Target=1.8°C in 2100
Primary Energy before 2040

Hedging actions
- Decrease of coal (mainly power plants, very slightly in industry)
- Sequestration by forests
- Hydro, wind
- N₂O and CH₄ abatement
- Moderate Demand reductions
- More nuclear (2030)

Non-hedging actions
- Power plants with CO₂ capture
- Energy substitution in end-use sectors
- H₂ for transport (weak, late)
Post-2040 abatement actions (for large values of Cs)

- **Power plants:** Hydroelectricity, Nuclear, Wind, Solar (very late), CCS
- **Transportation:** Large Substitution of RPPs by alcohols and gas (not by H2 and Elec)
- **Buildings:** Substitution of gas and RPPs by electricity, mainly for space heating
- **Industry:** Substitution of coal by gas (and electricity) in some industries
- **Demand** reductions (economic feedback)
Electricity production by fuel

Electricity production: BASECASE

- WIN
- TIDE
- SOL
- GEO
- BIO
- HYD
- NUC
- OIL
- GAS
- COA

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Electricity production by fuel (basecase)
Electricity production by fuel (hedging)
## Power plants

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## Power plants (cont.)

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Sensitivity analyses

Temperature change (2100) = 1.5°C

- Smallest achievable target
- Corresponds to Max (long term) = 2.1°C
- Extreme situation, feasible at very large cost
- GHG concentration must stay almost constant

\[
\text{Atm concentration (ppm CO}_2\text{-equiv)}
\]

Limit 2100 = 1.8 °C

Hedging strategies, R. Loulou, EMF-22 Wash DC 2008
Reduction of demands (examples)