New developments related to the World TIMES model: EMF-22 Project & Climate Module

Maryse Labriet, Richard Loulou
Group for Research in Decision Analysis (GERAD)
Montreal, Canada

Energy Technology Systems Analysis Programme
Semi-Annual Workshop
Kyoto, July 4, 2005

Outline

1. Progress made in the EMF-22 project
   • Stanford meeting, May 25-27, 2005
   • Progress accomplished so far in TIMES database and structure
   • Current and next work

2. The new “Climate Module” of TIMES
   • General equations
   • Implementation
   • Some results
Introduction

Starting
Collaboration started in 2004

EMF-22
Climate Policy Scenarios for Stabilization and Transition
⇒ Focus on comprehensive analyses of long-run climate stabilization policies under uncertainty as well as intermediate-term transition policies (2010-2040)

1st Meeting
Brussels, November 2004
- Define the work and the scenarios

2nd Meeting
Stanford, May 2005
- Consolidate the original objectives
- Confirm the Study Groups (SG)
- Outline a calendar for future activities

Four Study Groups

Hedging Transition Policies
Black Carbon
Land-Use

Rules of participation
Flexibility and freedom each participant has in choosing:
- membership in one or more SG’s
- among the several experiments proposed in each SG

No rigid base cases
⇒ each modeler ~ free to define its own reference case
⇒ alternate policy scenarios run by each modeler are relative to that modeler’s reference case(s)
**Hedging SG**

**Objective**
Evaluate hedging policies, i.e. “good” or “optimal” decisions taken while uncertainty prevails

**Uncertain parameter**
Climate sensitivity
Discrete probability distribution function:
L= 1.5°C (0.30), 2.5°C (0.40), 5°C (0.15), 8°C (0.15)

**Three experiments**
A: Full resolution of uncertainty in 2050
B: Partial resolution in 2050, full resolution in 2070
C: Partial resolution in 2030, full resolution in 2050

**Non-CO₂**
CO₂ concentration replaced by the concentration of all GHG gases expressed in CO₂-eq ⇒ avoids the modeling of life cycle of non-CO₂ GHGs

---

**Transition Policies SG**

**Objective**
Simulate a relatively large range of policies that could be applied in the 2010-2040 period

**Target-Driven Policies**
A reduction target (not yet defined) is specified in 2040 under a cap-and-trade regime, and the response of the model is analyzed, thus revealing sectoral and regional policies

**Policy-Driven Policies**
A set of policies* are specified and the effects on climate and costs are analyzed

*Eg: - sectoral caps and trade
- taxes and/or subsidies on commodities and/or technologies
- technology standards (car efficiency, building shell efficiency)
- portfolio standards (emission per kWh of electricity produced)
- impact of non-GHG policies on climate (local pollution limits, development oriented policies)
Land Use SG

Objective
Provide a detailed inventory and projections to 2050 of land uses and emissions as well as quantitative information on mitigation options

Approach similar to EMF-21, which provided non-CO₂ emissions and marginal cost curves for abating the emissions

Black and Organic Carbon SG

Objective
Study the effects of including black and organic carbon* in a cap-and-trade regime

* Produced during combustion of fossil fuels (RPP, coal) and biomass, warming (BC) / cooling (OC) potential

Progress accomplished so far

Transition of the database from the world multi-regional MARKAL to TIMES and testing the model

• Same structure
• New assumptions about input data: long-term energy service demands (based on POP and GDP projections), resources availability, specific energy policies & behaviors, future technologies (cost, efficiency), etc.
Reference Energy System (RES)

Fossil Fuel Reserves (oil, coal, gas)

Extraction

Biomass Potential

Renewable Potential

Nuclear

Carbon capture

Secondary Transformation

Electricity

C cogeneration

Heat

BIO**

WIN SOL (DEO TOL)

PTO

Fuels

End Use

HET

Trade

OPEC/ NON-OPEC regrouping

OLI***

GAS***

COA***

Electricity

Fuels

ELC***

Electricity

Cogeneration

Heat

BIO***

Nuclear

TOL

SNK

TOTCO2 (forests)

SNK

Trade

Climate module

CO2CONCatm,up,lo

RADFORCING

TEMPatm,lo

Progress accomplished so far

International trade

- Endogenous trading of natural gas, LNG, crude oil (and CO₂ permits) ⇒ endogenous quantities & prices
- Particularly challenging task for crude oil: control of oil annual production quantities by OPEC, so as to approximate the oil production decisions of the cartel ⇒ oil price from 3.8 to 8.7 $/GJ (22 to 55 $/bbl)

Climate module

- Integrated in the structure of the model
- Scenarios with bounded CO₂ concentration tested

Data handling tools (VEDA_FE, VEDA_BE): upgraded
**Sequestration**

1. EMF-22

**Capture**
- Power plants (pre- or post-combustion)
- Hydrogen plants
- Industry not incl

+50% elc price

**Transportation**
- From 3 to 55$/tC

**Geological, ocean & advanced storage**
- CUM=4157 GtC (1)
- From 4 to 12$/tC
- Depleted oil/gas fields
- Coal beds
- Saline aquifers (cheapest)
- Deep ocean
- + Mineralization (expensive)

**Terrestrial sinks**
- CUM=163 GtC (2)
- From 20 to 70$/tC
- Forestry, soils

(1) Calibrated to literature (Kauppi and Sedjo, 2001; Herzog et al., 1997)

(2) In the range proposed by IPCC, but very uncertain

Barriers:
- Needs for more R&D about CCS technologies, reservoirs and biological processes, risk of leakage, permanence

---

**Available Resources**

1. EMF-22

**CRUDE OIL (21)**

<table>
<thead>
<tr>
<th></th>
<th>TIMES</th>
<th>IPCC</th>
<th>MEAN</th>
<th>F5S</th>
<th>F50</th>
<th>F5</th>
<th>MERGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>168298</td>
<td>212193</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil sands (3)</td>
<td>33061</td>
<td>36020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bitumen (very heavy) (6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil shales (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NATURAL GAS (11)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>19897</td>
<td>17179</td>
<td>14395</td>
<td>9001</td>
<td>13111</td>
<td>20258</td>
<td>10086</td>
</tr>
<tr>
<td>Not conventional (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL OIL (21)</td>
<td>42315</td>
<td>35576</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>15202</td>
<td>13562</td>
<td>13562</td>
<td>9954</td>
<td>14454</td>
<td>21900</td>
<td>8928</td>
</tr>
<tr>
<td>Unconventional</td>
<td>27113</td>
<td>22014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**US geological survey**

<table>
<thead>
<tr>
<th></th>
<th>TIMES</th>
<th>IPCC</th>
<th>MEAN</th>
<th>F5S</th>
<th>F50</th>
<th>F5</th>
<th>MERGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL COAL (EJ)</td>
<td>168298</td>
<td>212193</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>19897</td>
<td>17179</td>
<td>14395</td>
<td>9001</td>
<td>13111</td>
<td>20258</td>
<td>10086</td>
</tr>
<tr>
<td>Unconventional</td>
<td>42315</td>
<td>35576</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Different types of reserves**

- Located reserves (known & recoverable)
- Reserves growth (to be developed)
- New discovery (probabilistic)
- Up to 3 steps for each type of reserves (cost)

**Potential**

- Gas and coal reserves of TIMES are consistent with other sources
- Oil reserves of TIMES are too high (non-conventional)
  - BUT based on reference case results, cumulative consumption of oil up to 2100 is ~ 25000 EJ ⇒ OK

**Potential of renewables also updated**
Current and future work

Non-CO₂ gases (2005)
• Calibration of CH₄ and N₂O emissions in the reference case
• Integration of the abatement options for
  - coal mining (7)
  - oil and natural gas sectors (4+15)
  - waste management (8)
  - manure management (2)
  - adipic & nitric acid industry (8)
• Use of cost curves provided by EMF-21

Hedging and climate sensitivity (2005-2006)
• Implementation of Stochastic Programming
• Simulations of uncertain long term stabilization targets using the climate module

• Simulation of Transition Policies

Role of ETSAP in EMF-22

Interest by EMF-22 in the active participation of ETSAP
• High degree of development of the TIMES model (integrated assessment with the Climate module)
• Technology oriented modeling approach (becoming a necessity for representing detailed policies)
• High visibility of ETSAP and its multi-country membership

Participation of ETSAP in Study groups
• Hedging
• Transition Policies

Benefit for ETSAP
• Data: other gases (EMF-21), latest knowledge on climate
• Visibility (publications)
• Reinforce collaboration with other BU and TD modelers
2. Climate Module

Approach: 3-step climate module

Equations
Adapted from the model proposed by Nordhaus and Boyer (1999)
Well documented + simple
Good approximation of those obtained from more complex climate models

Equations: concentration
Accumulation of CO₂ results from the transfer of carbon between:
- the atmosphere
- the quickly mixing upper ocean + biosphere
- the deep ocean (low mixing)
⇒ CO₂ flows in both directions between adjacent reservoirs

Linear

\[
M_{\text{atm}}(y) = E(y) + (1 - \phi_{\text{atm}-\text{up}}) M_{\text{atm}}(y-1) + \psi_{\text{atm-\text{atm}}} M_{\text{atm}}(y-1)
\]

(1)

\[
M_{\text{up}}(y) = (1 - \phi_{\text{atm-\text{up}}}) M_{\text{atm}}(y-1) + \psi_{\text{atm-\text{up}}} M_{\text{atm}}(y-1) + \psi_{\text{atm-\text{up}}} M_{\text{atm}}(y-1)
\]

(2)

\[
M_{\text{fo}}(y) = (1 - \phi_{\text{atm-\text{up}}}) M_{\text{atm}}(y-1) + \psi_{\text{atm-\text{fo}}} M_{\text{atm}}(y-1)
\]

(3)

with
- \( M_{\text{atm}}(y), M_{\text{up}}(y), M_{\text{fo}}(y) \): masses of CO₂ in atmosphere, in a quickly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively (GtC)
- \( E(y) \): CO₂ emissions (GtC)
- \( \phi_{ij} \): transport rate from reservoir \( i \) to reservoir \( j \) (\( i, j = \text{atm, up, fo} \)) from year \( y-1 \) to \( y \)
Equations: radiative forcing

Accumulation of GHGs leads to an increased radiative forcing at the surface of the earth.
Not controversial equation derived from empirical measurements and climate models.

Value of $\gamma$ (sensitivity to CO$_2$ concentration doubling): 4.1 W/m$^2$, 3.7 W/m$^2$ in IPCC (2001)

Exogenous forcing:
- All non-CO$_2$
- Only non-CO$_2$ not included in the CO$_2$-eq.
- Uncertainties: aerosols (cooling/warming)

$$\Delta F(t) = \gamma \frac{\ln(M_{\text{pre}}(t)/M_0)}{\ln 2} + O(t)$$

where:
- $M_0$ (i.e. CO2 ATM_Pref_IND) is the pre-industrial (circa 1750) reference atmospheric concentration of CO$_2$ = 596.4 GtC
- $\gamma$ is the radiative forcing sensitivity to atmospheric CO$_2$ concentration doubling = 4.1 W/m$^2$
- $O(t)$ (i.e. EXOFORCING(t)), is the increase in total radiative forcing at period $t$ relative to pre-industrial level due to anthropogenic GHG’s not accounted for in the computation of CO2 emissions. Units = W/m$^2$.

Equations: temperature increase

Higher radiative forcing warms the atmospheric layer, which then warms the upper ocean, gradually warming the deep oceans.

Two reservoirs: atmospheric + upper level of the ocean, deep ocean.

Temperature change = globally and seasonally averaged temperature in the atmosphere and the upper level of the ocean.

Not considered: regional and seasonal variability, precipitations, speed of change.

Value of $C_s$ (sensitivity to CO$_2$ concentration doubling: 1.5 to 4.5 °C, up to 10°C)

\[
\begin{align*}
\Delta T_{\text{atp}}(y) &= \Delta T_{\text{atp}}(y-1) + \sigma_1 \{ F(y) - \lambda \Delta T_{\text{atp}}(y-1) - \sigma_2 \{ \Delta T_{\text{atp}}(y-1) - \Delta T_{\text{low}}(y-1) \} \} \\
\Delta T_{\text{low}}(y) &= \Delta T_{\text{low}}(y-1) + \sigma_3 \{ \Delta T_{\text{atp}}(y-1) - \Delta T_{\text{low}}(y-1) \}
\end{align*}
\]

with:
- $\Delta T_{\text{atp}} = \text{globally averaged surface temperature increase above pre-industrial level,}$
- $\Delta T_{\text{low}} = \text{deep-ocean temperature increase above pre-industrial level,}$
- $\sigma_1 = \text{1-year speed of adjustment parameter for atmospheric temperature,}$
- $\sigma_2 = \text{coefficient of heat loss from atmosphere to deep oceans,}$
- $\sigma_3 = \text{1-year coefficient of heat gain by deep oceans,}$
- $\lambda = \text{feedback parameter (climatic retroaction) (\lambda = 4.1/C_s, C_s being the temperature sensitivity to CO}_2\text{ concentration doubling).}$
2. Climate Module

Variables and parameters

**True variables**
Three concentrations: atm, upper level of ocean+biosphere, deep ocean
Constraint is possible on atm concentration

**Reporting parameters**
Radiative forcing
Temperature changes: mean surface, deep ocean
Constraint on temp would result in non-linear non-convex optimisation pb

**Input parameters (default values are included)**
- CO₂ transfer rates between reservoirs
- Sensitivity of radiative forcing to the atm CO₂ concentration doubling
- Forcing of non-CO₂ GHGs?
- Heat transfer parameters
- Sensitivity of temperature to the atm CO₂ concentration doubling
- Historic (initial) values of concentrations and temperature increases
- Pre-industrial atmospheric concentration
- **Maximal CO₂ concentration**

GAMS Implementation and Reporting

- All required GAMS modules added to the code
- Climate Module implemented as a TIMES extension module

**Rem:** CO2ATM is interpolated on an annual basis
⇒ FORC, TATM and TLOW are calculated on an annual basis
⇒ Improvement in precision

- For reporting purpose, attributes have been added in the VEDA_BE report generator:
  - **CM_dt_forc:** Delta forcing
  - **CM_dt_tatm:** Temperature change in surface
  - **CM_dt_tlow:** Temperature change in deep layer
  - **VAR_co2tot:** Total CO₂ emissions by milestone year (in GtC)
  - **VAR_co2atm:** Mass of CO₂ in the atmosphere (in GtC)
  - **VAR_co2up:** Mass of CO₂ in the upper ocean layer (in GtC)
  - **VAR_co2lo:** Mass of CO₂ in the deep ocean layer (in GtC)
  - **EQ_co2concM:** Undiscounted annual shadow price of maximum CO₂ concentration constraint

See **www.etsap.org/documentation.asp**
Some illustrative results: Base case

- Inspired by the Common POLES-IMAGE (CPI)
- Moderate POP and GDP growth + technology progress
- Primary energy use continues to grow
- Gas & coal become the dominant energy carriers after 2050 (power plants and industry sector)
- Intermediate range of emissions (IPCC-SRES)

**Primary energy (Base case)**

- RNW
- HYDRO
- NUC
- OIL
- GAS
- COAL

**CO2 emissions**

- TIMES base case
- A1
- A2
- B1
- B2

**Emission vs concentration target**


**Higher long-term emissions and earlier action**

- Faster transition from fossil power plants to hydro and nuclear power plants
- Less renewable in LT
- Lower substitution to elc in end-use sectors in LT

Higher flexibility of concentration climate policies
Mitigation cost

Remarks
Value in 2080:
- 1538 $/tC with LT concentration limit
- 1869 $/tC with emission limit

Jump & high 2100 values: end-use constraints?

More results available (not shown): 450ppm, sequestration

TIMES documentation
www.etsap.org/documentation.asp