Analysis of the relative roles of supply-side and demand-side measures in tackling global climate change:

TIAM-MACRO with Variable Elasticity of Substitution

17.11.2016

Babak Mousavi
Markus Blesl

70th semi-annual IEA-ETSAP workshop – Madrid (Ciemat)
Analyzing the relative roles of mitigation measures in tackling global climate change

Outline

- Motivation
- Objective
- TIAM-MACRO
  - Variable elasticity of substitution
  - Normalization of production function
- Scenario Analysis
- Conclusions and outlook
Motivation


Challenge of meeting long term decarbonisation targets cost-effectively, not only requires the large scale uptake of low carbon technologies and fuels but also reductions in energy-services (Webler and Tuler, 2010; Sorrell, 2015).

As time passes firms and individuals respond more strongly to a unit increase of price of energy-services.
Objective

Research question

Analysis of the relative roles of the decarbonisation measures in tackling global climate change:

Including:

1) Macroeconomic impacts of climate mitigation policies.

2) The responsiveness of energy-services to their prices becomes stronger over time.

Methodology

TIAM-MACRO model with normalized production function and variable elasticity of substitution:

Coupling the energy system model (TIAM) with a macroeconomic model (MACRO):

Extensions:

Implementation of variable (time-dependent) elasticity of substitution

Normalization of the production function
Analyzing the relative roles of mitigation measures in tackling global climate change

Objective Function: Maximization of Negishi Weighted sum of regional consumptions (C):

\[ \max U = \sum_{t=1}^{T} \sum_{r} nwt_r \cdot dfact_{r,t} \cdot \ln(C_r,t) \]

For region \( r \), time period \( t \) and service-demand type \( dm \):

- \( PGDP_{r,t} \): Projected GDP
- \( P \): Marginal price
- \( EC_{r,t} \): Energy system cost [MACRO]
- \( qa \): Constant term of the QSF
- \( qb \): Coefficient of demands in QSF
- \( dfact \): Discount factor
- \( AESC_{r,t} \): Energy system cost of TIAM
- \( DET_{r,t} \): Energy service demand of TIAM
- \( AEEI_{r,t,dm} \): Autonomous energy efficiency improvement
- \( DET_{r,t,dm} \): Energy service demand [MACRO]
- \( NTX_r \): Trade in the numeraire good
- \( INV_r \): Investment
- \( AGDP_{r,t} \): Actual GDP
- \( vs \): Capital value share
- \( \rho \): Substitution constant (time independent)

\[ GDP\ Loss_{r,t} = \frac{(PGDP_{r,t} - AGDP_{r,t})}{PGDP_{r,t}} \times 100 \]

Energy model (TIAM)

Mcroeconomic model (MACRO stand alone)

Source: (Kypreos and Lehtila, 2013)
TIAM-MACRO

Energy model (TIAM)

\[ GDP\ Loss_{r,t} = \frac{(PGDP_{r,t} - AGDP_{r,t})}{PGDP_{r,t}} \times 100 \]

Production function:
\[ Y_{r,t} = a_{kl,r} K_{r,t}^{kpvs_r \cdot \rho_r} L_{r,t}^{(1-kpvs_r) \cdot \rho_r} + \sum_{dm} b_{r,t,dm} \cdot DEM_{r,t,dm}^{\rho_r} \]
\[ \rho_r = 1 - 1/E_{sub_r} \]

Source: (Kypreos and Lehtila, 2013)

Macroeconomic model (MACRO stand alone)

Objective Function: Maximization of Negishi Weighted sum of regional Consumptions (C):
\[ \max U = \sum_{t=1}^{T} \sum_{r} nw_{t,r} \cdot dfact_{r,t} \cdot \ln (C_{r,t}) \]
\[ C_{r,t} = Y_{r,t} - INV_{r,t} - EC_{r,t} - NTX_{r,t} \]
\[ AGDP_{r,t} = C_{r,t} + INV_{r,t} + NTX_{r,t} \]

\[ P_{GDP_{r,t}} \]

For region \((r)\), time period \((t)\) and service-demand type \((dm)\):

- **PGDP**: Projected GDP
- **NTX**: Trade in the numeraire good
- **AESC**: Energy system cost of TIAM
- **EC**: Energy system cost [MACRO]
- **qA**: constant term of the QSF
- **qB**: Coefficient of demands in QSF
- **dfact**: Discount factor
- **a, b**: Production function constants
- **vS**: Capital value share
- **AGDP**: Actual GDP

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Variability of elasticity of substitution

- In the MACRO model, elasticity of substitution represents the ease or difficulty of price-induced substitution between energy-service demands and the value-added pair capital and labor.

- The assumption of constant elasticity of substitution, which limits the reaction of economy to energy price changes, represents a unique function form of the production function over time.

- However, the constancy of this parameter may contain specification bias in the sense that as time passes firms and individuals may react differently to price changes.

- To address this issue, Revankar (1966) introduced the concept of Variable Elasticity of Substitution (VES) production function, in which the assumption of constancy is dropped.

- Several studies (e.g., Diwan, 1970; Lovell 1973; Zellner and Ryu, 1998; Karagiannis et al., 2005) analyzed the validity of VES production function using empirical data and found it a better function compared to CES and Cobb-Douglas.
Normalization of production function

- The production function constants are dependent to elasticity of substitution value(s):

\[ Y_{r,t} = \left[ akl_r \cdot K_{r,t}^{kpv_s_r \cdot \rho_r} \cdot L_{r,t}^{(1-kpv_s_r) \cdot \rho_r} + \sum_{dm} b_{r, dm} \cdot DEM_{r,t, dm}^{\rho_r} \right]^{1/\rho_r} \]

Applying first-order optimality condition for the base year (t = 0):

\[ b_{r, dm} = P_{r,0, dm} \cdot \left( \frac{DEM_{r,0, dm}}{Y_{r,0}} \right)^{1-\rho_r} \]

\[ akl_r = \frac{Y_{r,0}^{\rho_r} - \sum_{dm} b_{r, dm} \cdot DEM_{r,0, dm}^{\rho_r}}{K_{r,0}^{kpv_s_r \cdot \rho_r}} \]

- Impossible to implement variable elasticity of substitution.

- To tackle this issue, the production function is normalized (introduced by Klump and Grandville, 2000)

\[ Y'_{r,t} = \left[ akl_r^* \cdot K_{r,t}^{kpv_s_r \cdot \rho_r} \cdot L_{r,t}^{(1-kpv_s_r) \cdot \rho_r} + \sum_{dm} b_{r, dm}^* \cdot DEM_{r,t, dm}^{\rho_r} \right]^{1/\rho_r} \]

Where: \( Y'_{r,t} = \frac{Y_{r,t}}{Y_{r,0}} \)
\( K'_{r,t} = \frac{K_{r,t}}{K_{r,0}} \)
\( DEM'_{r,t, dm} = \frac{DEM_{r,t, dm}}{DEM_{r,0, dm}} \)

\[ b_{r, dm}^* = P_{r,0, dm} \cdot \left( \frac{DEM_{r,0, dm}}{Y_{r,0}} \right) \]

\[ akl_r^* = 1 - \sum_{dm} b_{r, dm}^* \]

- Normalization creates specific ‘families’ of functions whose members share the same baseline points.
### VES versus CES: scenario description

- In order to compare VES production function with CES production function, following two scenarios are defined:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Elasticity of substitution</th>
<th>1000 GtCO₂ budget (2020-2100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D (0.25)</td>
<td>0.25 (constant)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>2D (0.2-0.3)</td>
<td>0.2 - 0.3 (variable)</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

![Graph showing elasticity of substitution over time](image)

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VES versus CES: results

- changes of total global energy-service demand:

- The level of net effect of decarbonisation on GDP is related to the demand reduction possibility. Thus, higher/lower elasticity of substitution leads to lower/higher GDP-loss.

- Due to the assumed function of variable elasticity, service demand reduction of 2D (0.25) case is lower than that of 2D (0.2-0.3) before 2060 and higher after this year.

- In 2100, service demand reduction and GDP losses of 2D (0.2-0.3) are 23% higher and 12% lower than those of the other case, respectively.
## Scenario definition

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1000Gt carbon budget 2020-2100 1</th>
<th>25% higher potential of nuclear 2</th>
<th>25% higher potential of carbon storages 3</th>
<th>25% higher potential of biomass 4</th>
<th>25% higher potential of other renewables 4</th>
<th>Elasticity of substitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td></td>
</tr>
<tr>
<td>2D-DEM</td>
<td>✓</td>
<td>✗</td>
<td></td>
<td>✗</td>
<td>✗</td>
<td>~0</td>
</tr>
<tr>
<td>2D</td>
<td>✓</td>
<td>✗</td>
<td></td>
<td>✗</td>
<td>✗</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>2D+NUC</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✗</td>
<td>✗</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>2D+CCS</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>2D+REN</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>2D+REN+BIO</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>2D+All</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>0.2 – 0.3</td>
</tr>
</tbody>
</table>

1. To limit 2 degree temperature increase by the probability of more than 50%.

2. The initial potentials are mainly based on the high estimate of nuclear electrical generation capacity in 2013 report of International Atomic Energy Agency (IAEA).

3. The initial potentials of carbon storages are given based on the “best estimation” of econfys (2004).

4. The initial potentials of renewables are based on the assumed possible expansion pathways of different renewables which are provided by different studies (e.g. *IEA PV roadmap 2014, IEA CSP roadmap 2014, GWEC 2014, ...*).
What if energy-services do not respond to price changes

- In 2D-DEM scenario where the possibility of reducing energy-services is limited to almost zero, the global GDP-loss and marginal CO$_2$ abatement costs will be much higher than those of 2D case.
- In 2100, for example, GDP-loss is almost 93% and marginal abatement costs in 2D-DEM is about 95% higher that those of 2D.
• The total amount of the energy supply increases in all scenarios. Therefore:

• The speed of the energy efficiency improvement is slower than of demand drivers (e.g. GDP growth).

• Fossil fuels (especially coal) remain the main sources in the Base scenario.

• Decarbonisation scenarios have lower primary energy consumption compared to the Base case which is mainly a consequence of reduction in the demand of energy-services.

• In decarbonisation scenarios, the level of primary energy consumption varies (mainly) according to the demand of energy-services which is set by the price of energy-services.

6.6% 19.8% 29.7%
Differences in decarbonisation scenarios

- Relative changes compared to the 2D scenario (cumulated over 2020-2100):

  - Similar fossil fuel consumption in all scenarios is due to the inflexibility of some sectors in being completely decarbonized (e.g. some industrial processes).

  - Biomass with CCS found to be a vital and relatively cost-effective measure. However, its contribution is restricted to the capacity of carbon storages and the potential of Biomass.
Electricification of final consumption and CCS in power generation

- Share of decarbonized electricity in total generation in all mitigation scenarios (especially after 2030) is almost the same. This is mainly due to the high flexibility of this sector in being decarbonized.

- Policy recommendation:

Decarbonizing power generation and allowing electricity to substitute fossil fuels in inflexible energy uses (e.g. mobility) is a cost-effective decarbonisation strategy.
Decomposition of CO₂ emissions

The relative role of different measures in reducing total (cumulated) CO₂ emissions over the time horizon:

- In all the scenarios, renewables is found to be the main mitigation option.
- Higher contribution of service-demand reduction in the 2D compared to the others, denotes higher energy prices in this scenario caused by the climate target.
- The presence of fossil-fuel switching after the year 2090 (negative emissions) can be traced back to the inflexibility of some sectors in being completely decarbonized.
- Negligible share of efficiency improvement is due to the fact that the TIAM is an optimization model which selects cost-efficient technologies in all scenarios (including the base scenario).
- Without Bio-CCS, achieving the 2°C target seems to be barely possible.
Macroeconomic impacts of the climate policy

- Total global GDP-loss in 2D+All case is 23% less than that in 2D.
- From the global perspective, next to renewables (specially biomass), CCS is found to be relatively cost-effective mitigation measure. This can be traced back to the vital role of biomass with CCS.
Conclusions and Outlook

VES production function
- Possibility to consider dynamic reaction of economies to higher prices over the whole century.

Normalization of production function
- Better economic interpretation
- Necessary for modelling VES production function

A cost effective decarbonisation strategy
- Decarbonizing power generation and allowing electricity to substitute fossil fuels in inflexible energy sectors (e.g. mobility)

Feasibility of the 2D target
- Without deployment of a mixture of different mitigation options, it seems to be barely technically feasible and comes with huge macroeconomic impacts.

Role of energy-service demand reduction
- In all the mitigation scenarios, the cumulative contribution of service demand is more than 18%.
- Without the possibility of reducing demands, the GDP-Loss and CO2 marginal price can increase to more than 90%.

To address the uncertainty in elasticity of substitution
- Performing a sensitivity analysis on the elasticity of substitution as an epistemic uncertain factor.
References


Thank you!

Babak Mousavi

E-Mail am@ier.uni-stuttgart.de
Telefon +49 (0) 711 685-878-66

Universität Stuttgart
Institut für Energiewirtschaft und Rationelle Energieanwendung (IER)
Heßbrühlstraße 49a
70565 Stuttgart

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Appendix - TIAM (TIMES Integrated Assessment Model)

System boundaries
Solution concepts

Global-15 regions

2005 → 2100

Intermediate | Summer | Winter

Day | Night

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Appendix - TIAM (TIMES Integrated Assessment Model)

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03.06.201