Integrated Assessment Models

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IAMs

- An IAM is a model that contains a description of how the climate comes about, of how the economy evolves, and of how the two are integrated.
- An IAM can be used for assessing
  - implications of different policy proposals: positive analysis
  - which policy is best: normative analysis
  - the importance of a range of adaptation mechanisms, how different markets matter (insurance markets, international trade and international credit markets), migration, and so on.
- Policy advice must be quantitative.
- IAMs constitute the main formal tool used on the climate-economy arena.

What are not IAMs

- I IPCC's climate projections: they use assumptions about ("scenarios" for) future paths of fossil fuel use (future emissions), i.e., only analyze economy-to-climate channels.
    - and such projections, moreover, will then not be "consistent" – the realized climate will in general lead to other economic outcomes than assumed
- Models of the economy that include weather or climate variations but which do not specify how the climate depends on the economy,
- . . and many, many other models out there (which may be useful in other ways).

Existing IAMs

- Pioneering model: DICE (Dynamic Integrated model of the Climate and the Economy), by William Nordhaus (Yale U).
  - a one-region model describing both the climate and the economy
  - three blocks: climate model, carbon cycle, neoclassical economic model (solved with central planner).
- Development of DICE: RICE (Regional Integrated model of the Climate and the Economy), also by Nordhaus.
  - a number of regions, defined by geography/income level.
- Today there are many more IAMs in the academic literature. The IPCC doesn't have its own IAM (and little economics in general).

Optimal tax basics (Golosov et al. 2014)

- If damages are caused by the excess atmospheric CO_2 stock, S_t, we can write the optimal tax as the following object.

  $$\tau_t^* = -\sum_{j=0}^{\infty} \beta^j \frac{U'(C_{t+j})}{U'(C_t)} \frac{\partial Y_{t+j}}{\partial S_{t+j}} \frac{\partial S_{t+j}}{\partial E_t}$$

  the discounted value of the marginal damage incurred.

- Three terms every period:
  1. Discounting (both subjective and through consumption growth), $\beta^j \frac{U'(C_{t+j})}{U'(C_t)}$
  2. Marginal damages, $\frac{\partial Y_{t+j}}{\partial S_{t+j}}$.
  3. How emission in t affect the carbon stock in period $t+j$, $\frac{\partial S_{t+j}}{\partial E_t}$.

Damages and climate

- With log utility and a (approximately) constant savings rate $\frac{U'(C_{t+j})}{U'(C_t)} = \frac{Y_t}{Y_{t+j}}$.
- Recall we could approximate $1 - D(S_t) \simeq e^{-\gamma(S_t)}$ – with marginal GDP-loss as a share of net GDP being constant at γ, i.e., $\frac{\partial Y_{t+j}}{\partial S_{t+j}} = -\gamma Y_{t+j}$.
- Using the simple depreciation function $d(s) = 1 - (\varphi_L + (1-\varphi_L)\varphi_0 (1-\varphi)^s)$ for how much of a unit of CO_2 remains airborne s periods after if was emitted, $\frac{\partial S_{t+j}}{\partial E_t} = \varphi_L + (1-\varphi_L)\varphi_0 (1-\varphi)^j$.
- Then $\tau_t^* = -\sum_{j=0}^{\infty} \beta^j \frac{U'(C_{t+j})}{U'(C_t)} \frac{\partial Y_{t+j}}{\partial S_{t+j}} \frac{\partial S_{t+j}}{\partial E_t}$

$$
\begin{aligned}
&= \sum_{j=0}^{\infty} \beta^j \frac{Y_t}{Y_{t+j}} \gamma Y_{t+j} \left(\varphi_L + (1-\varphi_L)\varphi_0 (1-\varphi)^j \right) \\
&= Y_t \bar{\gamma}_t \left(\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-(1-\varphi)\beta} \right)
\end{aligned}
$$

A simple formula

$$\tau_t^* = Y_t \bar{\gamma}_t \left(\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-(1-\varphi)\beta} \right)$$

- Tax proportional to current GDP, damage parameter and duration of carbon in atmosphere (term in parenthesis).
- Independent of technology, future output, alternative energy, carbon storage, uncertainty about γ .....
- Surprisingly robust! (Barrage, 2013).
- Can easily be adapted to non-geometric discounting! (Iverson, 2013). Due to objective being objective linear in S.
- With riskaversion and balanced growth g_y- replace β with $\beta(1+g_Y)^{1-\sigma}$ in formula but $\sigma >> 1$ seems unreasonable!

Our IAM

- Our IAMs: a core, one-region model and multiregion versions.
- Simple and tractable – **Analytical Integrated Assessment Model.** All endogenous variables but price of conventional oil in closed form.
- Easy to integrate with advanced climate models.
- Simple to extend, more energy sources (4 in benchmark), allow ETC, more regions, short-run inflexibility, ...

The economy: production

- r regions: region 1 is the sole supplier of *conventional oil* (only produces oil), regions $i \in \{2, ..., r\}$ are *oil consumers*.
- **Oil supplying region** only sells oil ($e_{1,i,t}, i \in \{2, ..., r\}$) from its finite oil reserve (R_t), extracted at zero cost,

$$R_{t+1} = R_t - \sum_{i=2}^{r} e_{1,i,t}, R_t \geq 0 \forall t.$$

- **Oil consuming regions** produce common final good, representative firm production function

$$Y_{i,t} = A_{i,t} L_i^{1-\alpha-\nu} K_{i,t}^{\alpha} E_{i,t}^{\nu}$$

$A_{i,t}$ increases over time due to labor augmenting technical change and population growth and is affected by climate change. L_i is (initial, raw) labor, $K_{i,t}$ the capital stock and *energy services* $E_{i,t}$ is a composite of different energy inputs.

The economy: energy

- **Energy services** provided competitively by representative firm in each oil consuming region. Two-layer nested CES:
  1. **Oil** is a CES composite of I different types of liquid fossil fuels; conventional imported from the oil region $(e_{1,i,t})$ and non-conventional regionally produced varieties $\left(e_{n+j,i,t}\right)$ (in some regions).

     $$O_{i,t} = \left(\lambda_1^{oil} e_{1,i,t}^{\rho_h} + \sum_{j=1}^{I} \lambda_{j+1}^{oil} \left(e_{n+j,i,t}\right)^{\rho_h}\right)^{\frac{1}{\rho_h}}$$

     with elasticity $\frac{1}{1-\rho_h} >> 1$ (10 in calibration).
  2. **Energy services** is a CES composite of oil and regionally produced other energy sources (coal and non-fossil ones).

     $$E_{i,t} = \mathcal{E}\left(O_{i,t}, e_{2,i,t} \ldots, e_{n,i,t}\right) = \left(\lambda_1 O_{i,t}^{\rho} + \sum_{k=2}^{n} \lambda_k \left(e_{k,i,t}\right)^{\rho}\right)^{\frac{1}{\rho}}$$

     where $e_{2,i,t}, ..e_{n,i,t}$ are different kinds of fuels and other energy sources produced regionally.

Resource constraints

- Conventional oil traded globally at price $p_{1,t}$.
- Other energy sources $(e_{k,i,t})$ produced in each region at cost $p_{k,i,t}$.
- Aggregate resource constraint for **oil consuming regions**

$$C_{i,t} + K_{i,t+1} = Y_{i,t} - p_{1,t} e_{1,i,t} - \sum_{k=2}^{n} p_{k,i,t} e_{k,i,t}$$

- Capital depreciates fully between periods, which will be a decade long. Short-run dynamics disregarded.
- Resource constraints for **oil supplying region**

$$C_{1,t} = p_{1,t} \left(R_t - R_{t+1} \right)$$

where R_t is remaining oil reserves.

Consumers and markets

- **Representative consumer** in each region i with preferences

$$E_0 \sum_{t=0}^{\infty} \beta^t \log(C_{i,t}).$$

- In **oil producing region**, consumer owns the oil producing firm that maximizes profits. Consumes firm profits.
- In **oil consuming regions**, consumer owns both types of firms, supplies labor and capital to the firms on competitive markets.
- Decides each period how much to consume and save in the form of next periods capital stock.
- Perfect and complete regional markets and global market for oil. International market for other fuels allowed (amounts to setting prices equal).

Emission and carbon circulation

- Energy source k emits g_k units of carbon per unit of the energy source. Fossil fuels measured in carbon content ($g_k = 1$).
- Aggregate regional emissions

$$M_{i,t} = \sum_{j=1}^{n+l} g_j e_{j,i,t}$$

- Three-reservoir carbon circulation:

$$\begin{aligned}
S_t - S_{t-1} &= -\phi_{12} S_{t-1} + \phi_{21} S^U_{t-1} + E_{t-1} \\
S^U_t - S^U_{t-1} &= \phi_{12} S_{t-1} - (\phi_{21} + \phi_{23}) S^U_{t-1} + \phi_{32} S^L_{t-1} \\
S^L_t - S^L_{t-1} &= \phi_{23} S^U_{t-1} - \phi_{32} S^L_{t-1}.
\end{aligned}$$

Climate and damages

- Two-temperature climate model

$$\begin{aligned} T_t - T_{t-1} &= \sigma_1 \left(\frac{\eta}{\ln 2} \ln \left(\frac{S_{t-1}}{S_0} \right) - \kappa T_{t-1} - \sigma_2 \left(T_{t-1} - T^L_{t-1} \right) \right) \\ T^L_t - T^L_{t-1} &= \sigma_3 \left(T_{t-1} - T^L_{t-1} \right) \end{aligned}$$

- Damages: borrow from Golosov et al. (2014) (but can easily be changed to any function of temperature and or carbon stock). Aggregate TFP is a negative function of S_{t-1} (and exogenous trend $z_{i,t}$);

$$A_{i,t} = e^{(z_{i,t} - \gamma_i S_{t-1})}$$

- γ_i is **lost share of GDP flow in region *i* per unit of excess carbon** in atmosphere.

Government and taxes

- In each region, a carbon tax $\tau_{i,t}$ is set per unit of fossil emissions.
- Fuel price including taxes $\hat{p}_{k,i,t} = \tau_{i,t} g_k + p_{k,i,t}$.
- Tax revenues redistributed to households *proportionally* to income. Household income is $(1 + \Sigma_{i,t})\,(w_{i,t} L_i + r_{i,t} K_{i,t})$ where $\Sigma_{i,t}$ is tax revenues divided by GDP (net of fuel costs).
  - With lumps distribiution, the savings rate would depend on carbon taxes (but very little).

Equilibrium – production

- Regional competitive energy service provider minimizes cost of providing energy services.
- Yields regional fuel mix and an exact price index in closed form given fuel prices and carbon taxes.
- In oil consuming regions, representative final good firm maximize profits taking price of energy services $P_{i,t}$, wages $w_{i,t}$ and rental cost of capital $r_{i,t}$ as given.
- Yields output and prices in closed form expressions.

Equilibrium – consumers

- Optimum for representative household in **oil producing region** yields supply of conventional oil as a constant share of remaining stock.

  $$R_{t+1} = \beta R_t, \; C_{1,t} = p_{1,t} \left(1 - \beta\right) R_t$$

  Income and substitution effects of current price on saving oil for later cancels, making oil supply completely price inelastic! Recall cake-eating problem.
- Representative household in **oil consuming regions** maximizes expected utility taking prices and tax receipts as given.
- Optimum implies a **constant savings rule** $s = \frac{\alpha\beta}{1-\nu}$. Convenient!

Equilibrium – recursive solution

- Allocation in t recursively determined by pre-determined state variables $\left\{K_{i,t}, R_t, T_{t-1}, T^L_{t-1}, S_{t-1}\right\}$ and satisfies:
  - Constant savings rate $\frac{\alpha\beta}{1-\nu}$ of net income (labor and capital income plus carbon tax revenues).
  - Supply of conventional oil $e_{1,t} = (1-\beta) R_t$
  - Oil composite price

$$P^O_{i,t} = \left(\left(\lambda^{oil}_1\right)^{\frac{1}{1-\rho_h}} \hat{p}_{1,i,t}^{\frac{\rho_h}{\rho_h-1}} + \sum_{j=1}^{I} \left(\lambda^{oil}_{j+1}\right)^{\frac{1}{1-\rho_h}} \left(\hat{p}_{n+j,i,t}\right)^{\frac{\rho_h}{\rho_h-1}} \right)^{\frac{\rho_h-1}{\rho_h}}$$

  - Energy service price

$$P_{i,t} = \left((\lambda_1)^{\frac{1}{1-\rho}} \left(P^O_{i,t}\right)^{\frac{\rho}{\rho-1}} + \sum_{j=2}^{n} \left(\lambda_j\right)^{\frac{1}{1-\rho}} \left(\hat{p}_{j,i,t}\right)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}$$

  - Energy service use $E_{i,t} = \left(\nu \frac{e^{\left(z_{i,t}-\gamma_{i,t}S_{t-1}\right)} L_{i,t}^{1-\alpha-\nu} K_{i,t}^{\alpha}}{P_{t,i}}\right)^{\frac{1}{1-\nu}}$

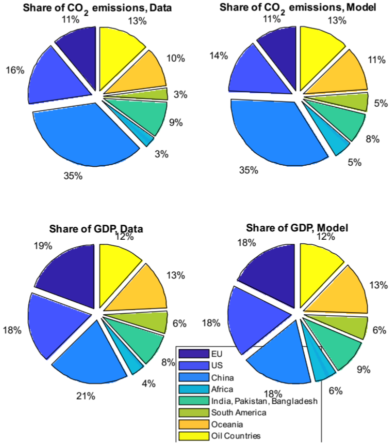
Equilibrium – recursive solution (cont.)

- Oil composite use $O_{i,t} = E_{i,t}\left(\lambda_1 \frac{P_{i,t}}{P^o_{i,t}}\right)^{\frac{1}{1-\rho}}$
- Oil use of different types $e_{j,i,t} = O_{i,t}\left(\lambda_j^{oil} \frac{P^o_{i,t}}{\hat{p}_{j,i,t}}\right)^{\frac{1}{1-\rho_h}}$
- Use of other energy sources $e_{j,i,t} = E_{i,t}\left(\lambda_j \frac{P_{t,i}}{\hat{p}_{j,i,t}}\right)^{\frac{1}{1-\rho}}$
- State variable l-o-m $K_{i,t} = \frac{\alpha\beta}{1-\nu}\left(1+\Gamma_{i,t}\right)\hat{Y}_{i,t}$, $R_{t+1} = \beta R_t$ and $\left\{T_{t-1}, T^L_{t-1}, S_{t-1}, S^U_{t-1}, S^L_{t-1}\right\}$ from Climate-Carbon module.
- Everything but oil price $p_{1,t}$ determined by closed-form expressions. Solve in Excel in a second. Can have an arbitrary number of regions and fuels.

Calibration economy

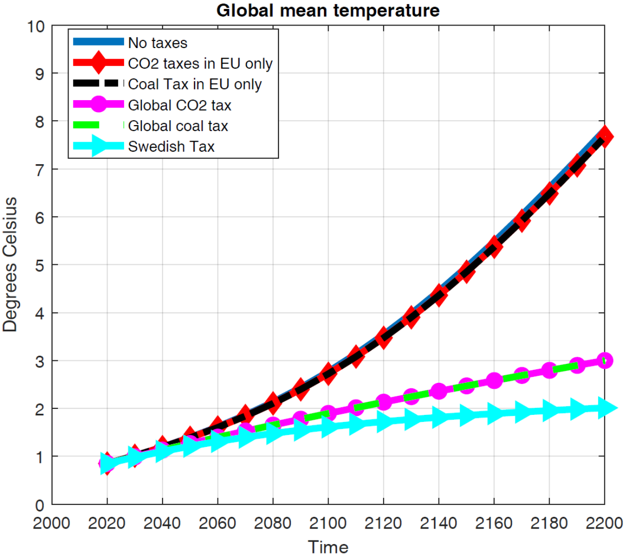
- **8 regions**, oil producers (OPEC+Russia), Europe, U.S., China, India+, South America, Africa and Oceania.
- 4 **sources of energy**, oil (finite supply 330 GtC), fracking in the U.S., coal and renewables. Latter three perfectly elastic at prices $p_{k,i,t}$ in terms of output goods. Constant over time in benchmark (equal tech trends).
- Standard assumptions for discounting and final good production.
- **Elasticity of substitution** between oil, coal and green energy sources $\sigma = \frac{1}{1-\rho} = 0.95$ (Stern, 2012). In oil composite EoS=10.
- Energy suppliers production function calibrated based on observed market prices and quantities. Cost of coal production allowed to differ across regions (WEO). **Price renewables = current price of oil**.
- Cost of producing oil from fracking \$US 40/barrel, conventional oil 0.
- Productivity catch up developing regions, but not fully. 25% of gap per decade.

Share of GDP and emissions



Experiments - taxes

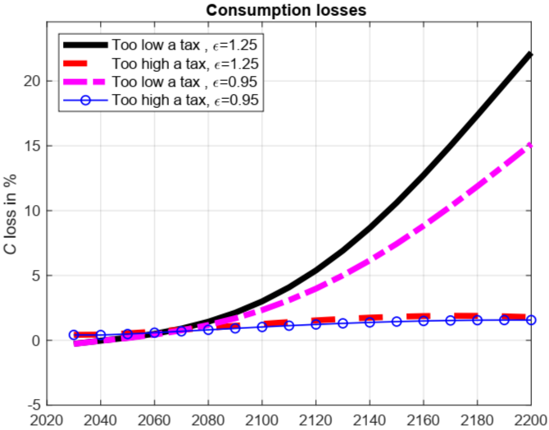
- Compare global (European only) carbon tax and coal tax. Set a modest global tax at 77 US$ per ton carbon ("optimal" in Golosov et al. 2014). Increases by 2.2% per year ($\approx$ follows global GDP). Less than half current EU ETS Price. Corresponds to 5 cents/liter gasoline.
- Summary of results:
  - Global coal tax at modest level is effective in mitigating climate change – tax on oil or EU-only taxes not effective.
  - Marginal effect of taxes on climate decrease in tax rate.


Global mean temperature
No taxes
CO2 taxes in EU only
Coal Tax in EU only
Global CO2 tax
Global coal tax
Swedish Tax
Degrees Celsius
0
1
2
3
4
5
6
7
8
9
10
2000
2020
2040
2060
2080
2100
2120
2140
2160
2180
2200
Time

Robust policy – cost of policy mistakes

- Range of uncertainty from IPPC 5th – climate sensitivity 1.5 to 4.5 $^\circ C$. (This has been updated slightly in IPCC 6th report; 67% 2.5-4$^\circ C$ and 90% 2-5$^\circ C$)
- Range for economic sensitivity calculated from metastudy by Nordhaus an Moffat (2017).
- Rather similar width of uncertainty in terms of range of implied optimal tax (Hassler et al. 2018).
- Optimal tax with low climate sensitivity and low economic sensitivity 6.9 US$\$/tC$. With high economic and high climate sensitivity it is 264 US$\$/tC$.
- One tC produces 3.66 tCO_2 and one liter of gasoline contains 0.6 kgC. So these two taxes corresponds to 1.9 and 72$\$/tCO_2$ or 0.4 and 16 cents per liter of gasoline.
- Calculate loss in terms of lost consumption from two policy mistakes:
    - setting the high tax when the low is optimal, vs.
    - setting the low tax (≈ 0) when the high is optimal.

Asymmetric losses from policy mistakes



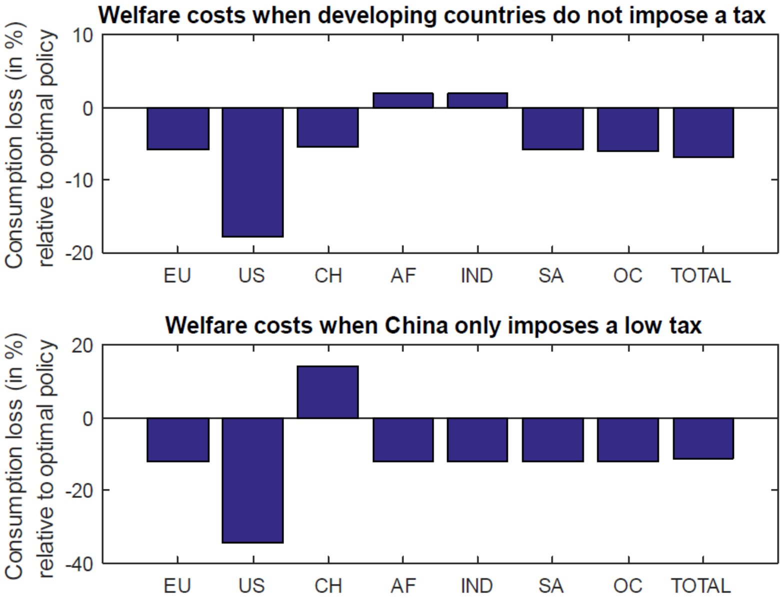
Intuition for asymmetry (Hassler et al. JEEA 2021)

- Tax has two effects;
  - given climate change it distorts the use of fuels (**M**arginal **C**ost of taxation).
  - it reduces emissions and damages from climate change (**M**arginal **B**enefit of taxation).
- Taxes has first order effects on use but only second order on costs at a zero tax level. $MC\left(0\right)=0$, $MB\left(0\right)>0$ if damages are positive.
- Thus, a moderate tax is a good insurance (low cost, high potential value) against high sensitivities.
- A good insurance is a robust policy.

Cost of departures from uniformity

- Suppose we want to achieve no more than $2.6^{\circ}C$ heating over coming 250 years (optimal with mid-point values of climate and economic sensitivities).
- Global tax should then be 77US\$/tC.
- Analyze two departures from uniformity:
    1. Africa and India don't tax.
    2. China introduce only a very low tax (15% of "optimal").
- Rest of world then has to be more aggressive (5, vs 20 times higher tax rate).
- Use model to calculate welfare costs in terms of consumption.

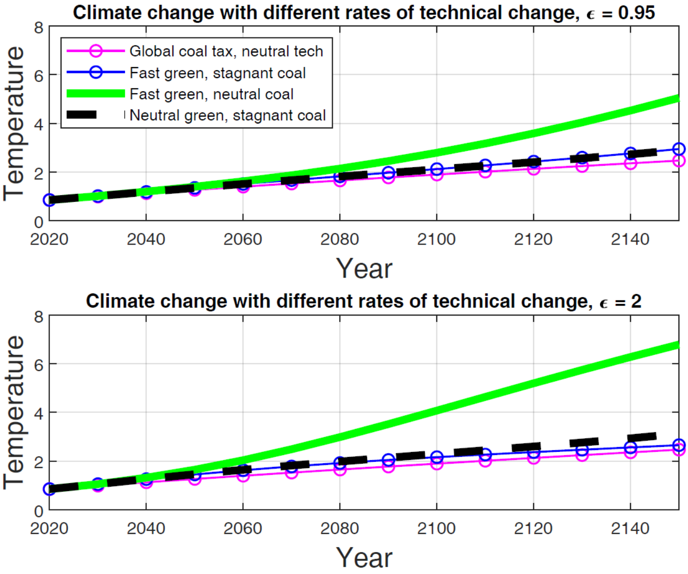
Loss from non-uniform taxation



Green innovations as substitute for tax

- Subsidies to green technologies, making green energy cheaper over time, has been suggested as a substitute for a tax.
- Analyze consequences of falling green energy prices (2% per year) and/or slower technical change in coal-industry making coal 2% more expensive over time. No taxes.

Faster green technical change



Conclusion

- There are productive ways for macroeconomics to be helpful in the area of climate change.
- In particular, a stripped-down IAM is used in order to obtain quantitative answers: a cost-beneft evaluation of bad, but realistic, policies.
- Some of the answers were surprising to us:
    - best available estimates suggest the policy errors are highly asymmetric, leading one to favor a high tax on carbon
    - quite costly if some regions don't participate in curbing emissions. Increasing marginal costs make compensation costly. Don't let China, India and Africa of the hook.
    - to subsidize green energy as a substitute for taxing coal appears very hazardous (for the climate).
    - Carbon taxes are effective – also if lower than optimal, but they need to have broad coverage.
    - Taxes on conventional oil/gas irrelevant for the climate.
    - Important that coal prices increase over time – technical change there must stop.