Integrated Assessment in a Multi-region World with Multiple Energy Sources and Endogenous Technical Change

John Hassler, Per Krusell, Conny Olovsson and Michael Reiter
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Climate and Economics

- Natural science community: it is "beyond reasonable doubt" that the global climate is affected by human activities (fossil fuel burning).
- Emissions constitute an *externality*.
  - Firms and households that emitt CO_2 do not pay for the cost that are associated with these emissions.
  - CO_2 mixes quickly in the atmosphere and affects the climate everywhere (but differently).
- The presence of externalities implies a market failure.
  - Unregulated markets cannot be expected to allocate resources efficiently.
  - The emitter needs an incentive to take into account external effects (e.g., by having to pay a tax).

Easy in principle - difficult in practice

- Policy advice must be quantitiative.
- Carbon stays in atmosphere very long time and affects (differently) all parts of the world.
- Large and hard-to-quantify uncertainty both about climate sensitivity and economic sensitivity.
- We need an integration of a global dynamic macro model and a climate model – an Integrated Assessment Model.
- Must be reasonably consistent with observed facts about the world.
- Since our economy is a market economy, the model should be too.
- Running different scenarios provide important information also when uncertainty cannot be quantified.

Outline of talk

1. Present a global Integrated Assessment Model with heterogenous climate damages and several sources of energy. Simple and tractable – **Analytical Integrated Assessment Model.** Easy to integrate with advanced climate models and simple to extend – today;
    1. multiple energy sources with different degrees of substitutability – fracking.
    2. endogenous technical change in energy production.
2. Calibration of the model for exogenous growth in TFP and energy production.
3. Experiments:
    1. different tax schemes.
    2. different trends in production costs of energy sources (fossil vs. renewables).
4. Endogenize directed technology for production of different energy sources to analyzes of how R&D and carbon taxes interact.

The economy

- r regions: region 1 is the sole *oil supplier* (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, 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:2

- **Energy services** provided competitively by representative firm in each oil consuming region:

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

where $e_{1,i,t}$ import of oil to region i, $e_{2,i,t}, ..e_{n,i,t}$ produced regionally at cost with linear production function using the final good as input.

- **Extension** with nested CES representing fracking, oil is a composite of imported conventional oil and non-conventional regionally produced fuels

$$e_{1,i,t} = \left(I \left(\sum_{k=1}^{I} \lambda_{1,k} \left(e_{1,k,i,t} \right)^{\rho_h} \right)^{\frac{1}{\rho_h}} \right)$$

with elasticity $\frac{1}{1-\rho_h} >> 1$ (10 in calibration).

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**

$$\begin{aligned} C_{i,t} + K_{i,t+1} &= Y_{i,t} - p_{1,t}e_{1,i,t} - \sum_{k=2}^{n} p_{k,i,t}e_{k,i,t} \\ &= (1-\nu)\, Y_{i,t} = \hat{Y}_{i,t} \end{aligned}$$

- Capital depreciates fully between periods, which will be a decade long.
- 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, she 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 produces g_k units of carbon emissions per unit of the energy source. Measure fossil fuels in carbon content, for these $g_k = 1$.
- Aggregate regional emissions

$$M_{i,t} = \sum_{k=1}^{n} g_k e_{k,i,t}$$

- Golosov et al. (2014), building on IPCC, show that a simple three parameter depreciation model for the atmospheric stock of excess carbon well captures advanced carbon circulation models.

$$S_t = \sum_{s=0}^{\infty} (1 - d_s) \sum_i M_{i,t-s}$$

where

$$1 - d_s = \varphi_L + (1 - \varphi_L)\, \varphi_0 \,(1 - \varphi)^s$$

measures the share of emissions remaining in atmosphere s periods after it was emitted.

Climate and damages

- Climate: borrow two-temperature (T_t, T_t^L) energy budget model from DICE/RICE.

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

- Damages: borrow from Golosov et al. (2014). 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.
- Consider two cases (matters a lot with ETC):
  1. *ad-valorem* taxes implying fuel price including taxes $\hat{p}_{k,i,t} = (1 + \tau_{i,t} g_k)\, p_{k,i,t}$ and
  2. *per unit* tax implying 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. Houseold 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).

Equilibrium – production

- Regional competitive energy service provider minimizes cost of 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 expresions.

Equilibrium – consumers

- Optimum for representative household in oil producing country yields (income and substitution effects cancel) supply of conventional oil a constant share of remaining stock

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

- 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 - summary

- Allocation in t recursively determined by pre-determined state variables $\left\{K_{i,t}, R_t, T_{t-1}, T_{t-1}^L, S_{t-1}\right\}$ and satisfies:
  1. Constant savings rate $\frac{\alpha\beta}{1-\nu}$ of income (labor and capital income plus carbon tax revenues).
  2. (energy service price) $P_{i,t} = \left(\sum_{k=1}^n \hat{p}_{k,i,t}^{\frac{\rho}{\rho-1}} \lambda_k^{\frac{1}{1-\rho}}\right)^{\frac{\rho-1}{\rho}}$
  3. (energy service use) $E_{i,t} = \left(\nu \frac{e^{\left(z_{i,t}-\gamma_{i,t}S_{t-1}\right)} L_{i,t}^{1-\alpha-\nu} K_{i,t}^{\alpha}}{P_{t,i}}\right)^{\frac{1}{1-\nu}}$
  4. (energy fuel use) $e_{k,i,t} = E_{i,t}\left(\frac{P_{t,i}\lambda_k}{\hat{p}_{k,i,t}}\right)^{\frac{1}{1-\rho}}$
  5. (oil equilibrium) $\sum_{i=2}^r e_{1,i,t} = (1-\beta) R_t$
  6. (state variable l-o-m) $K_{i,t} = \frac{\alpha\beta}{1-\nu}\hat{Y}_{i,t}$, $R_{t+1} = \beta R_t$ and $S_t = \sum_{s=0}^t (1-d_{t-s}) \sum_i M_{i,s}$, $\left\{T_t, T_t^L\right\} = NH\left(T_{t-1}, T_{t-1}^L, S_{t-1}\right)$
- 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

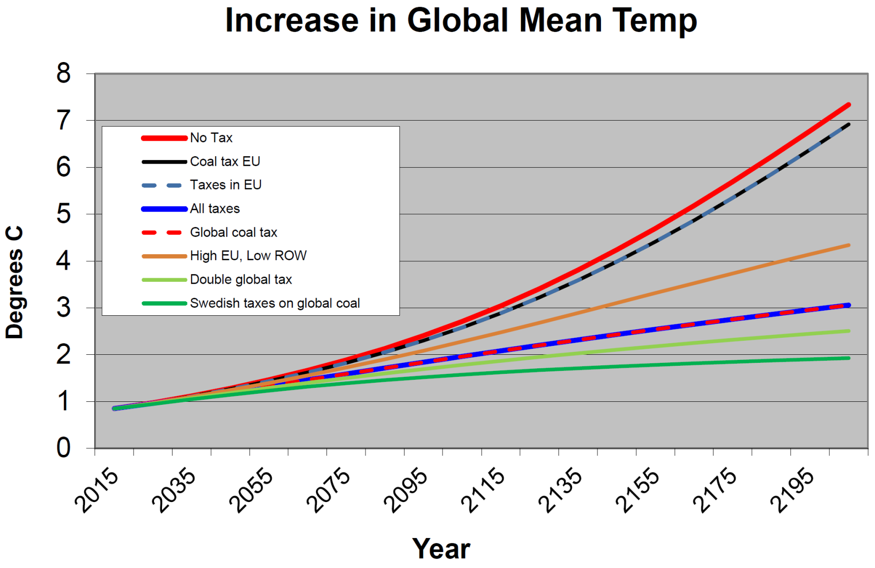
- **6 regions**, oil producers, Europe, U.S., China, India and Africa.
- **3 sources of energy**, oil (finite supply 330 GtC), coal and renewables. Latter two perfectly elastic at prices $p_{k,i,t}$ in terms of output goods. Constant over time in benchmark (equal tech trends).
- Standard assumptions 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).
- 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**.
- In extension with **fracking technology**, cost of production \$US 40/barrel in the U.S. and \$US 60/barrel in China. Elasticity between oil and fracked fuels = 10.
- Damages and climate paramaters from Nordhaus & Moffat (2017) and RICE-2016.

Questions - exogenous technology

- How is allocation affected if a global carbon or coal tax is introduced? If only Europe introduces it?
- What happens if trends in cost of energy sources change (coal vs. renewable)?
- What if we extend the production function for energy services by allowing some fuels to be costly to produce and highly substitutable with oil (fracking)?
- Focus on amount of global warming and distributional consequences (between Europe, US, China, India, Africa and Oil producers).

Experiments - taxes

- Compare global (European only) carbon tax and coal tax. Set to the global tax 77 US$ per ton carbon (optimal in Golosov et al. 2014). Increases by 2% per year ($\approx$ follows global GDP). Close to current ETS Price.
- Summary of results:
  - Global coal tax is effective in mitigating climate change – tax on oil or EU-only taxes not effective.
  - Also a modest (realistic) coal tax is fairly effective (77 US$ in Europe, elsewhere 77/4).
  - Africa and India gains the most global carbon/coal tax. US, EU and China also gains but less.
  - Oil producers loose a lot from oil tax (which doesn't change the climate) but not (much) from a coal tax..


Increase in Global Mean Temp
Degrees C
8
7
6
5
4
3
2
1
0
No Tax
Coal tax EU
Taxes in EU
All taxes
Global coal tax
High EU, Low ROW
Double global tax
Swedish taxes on global coal
2015
2035
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2075
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2135
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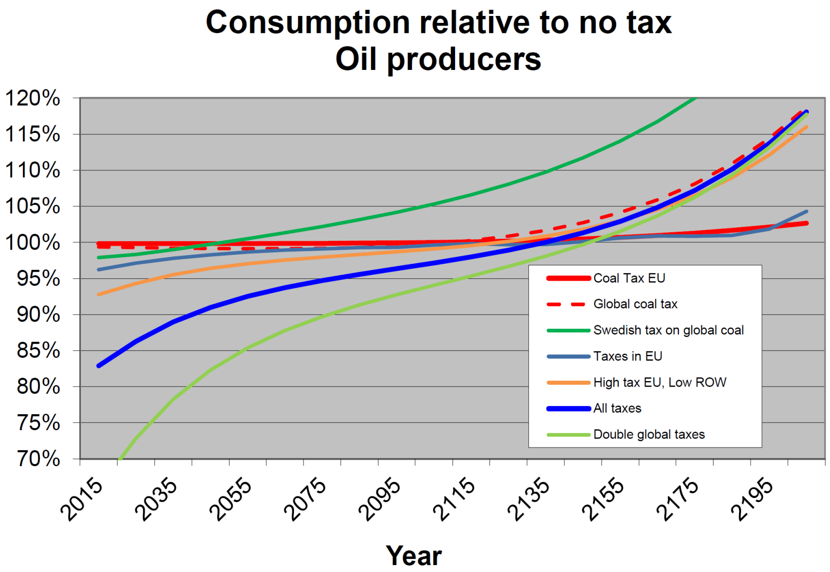
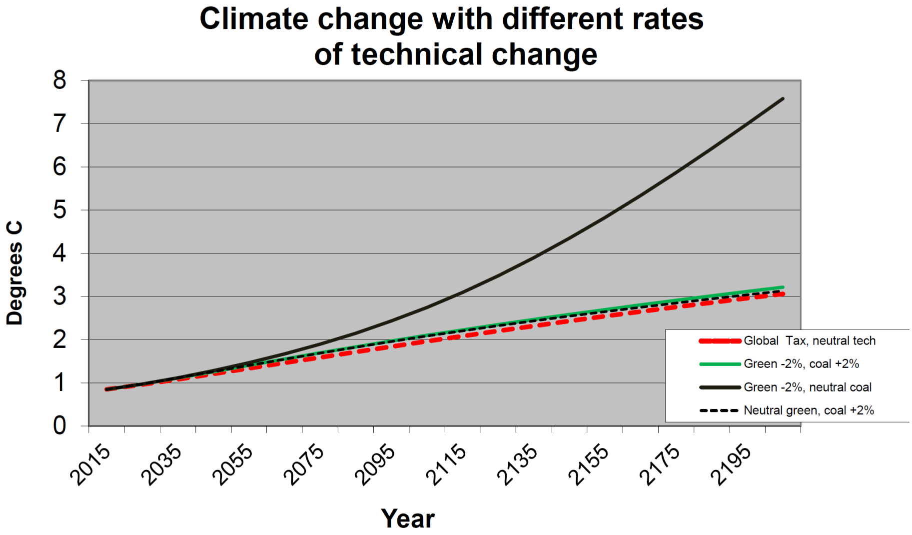
Year


Consumption relative to no tax
Oil producers
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
70%
2015
2035
2055
2075
2095
2115
2135
2155
2175
2195
Year
Coal Tax EU
Global coal tax
Swedish tax on global coal
Taxes in EU
High tax EU, Low ROW
All taxes
Double global taxes

Experiment - exogenous tech change

- Assume faster exogenous tech change in green and stagnant in coal. 2% yearly reduction in relative price of renewables and 2% increase in relative price of coal. Recall output good is numeraire, so since output grows 2% per year, a stagnant coal technology implies 2% higher prices per year.
- Summary of results:
  - Tech change achieves approximately the same as a global coal tax.
  - Only green tech change does little for climate, relative price of coal must increase!


Climate change with different rates
of technical change
Degrees C
0
1
2
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6
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2015
2035
2055
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2115
2135
2155
2175
2195
Year
Global Tax, neutral tech
Green -2%, coal +2%
Green -2%, neutral coal
Neutral green, coal +2%

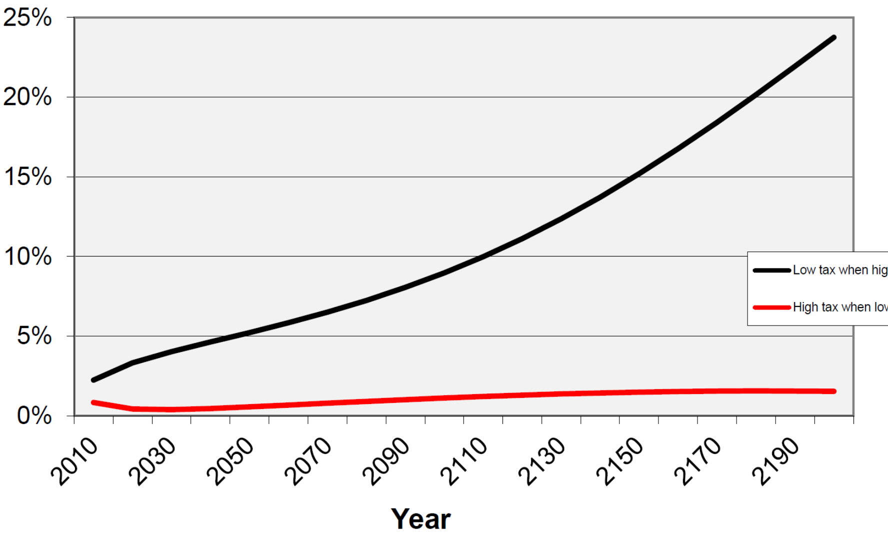
Fracking extension

- A fuel that is highly substitutable with oil can be produced in USA and China.
- Summary of results:
  - More global warming both with and without taxes.
  - A coal tax is not sufficient – (non-conventional) oil must be taxed.

Policy mistakes

- We don't know if climate sensitivity is 1.5 or 4.5 degrees C.
- The economic sensitivity is equally uncertain.
- It's hard even to assign probabilities.
- IAM useful anyway.
- Two types of policy mistakes:
  - Base policy on high sensitivities, eventually turns out to be the opposite.
  - Base policy on low sensitivities, eventually turns out to be the opposite.
- What are the costs of these policy mistakes?

Consumption loss



Endogenous technical change

- Directed technical change in extraction key for climate change. Need to endogenize.
- Here – consider interaction with energy taxes (rather than R&D subsidies).
- Stylized model, but can be extended and more realistically calibrated.
- Extention only affects energy service providers, nothing else is changed in model (including simple recursive structure).

Energy service providers

- Representative energy service providers now has **a second choice** – how to allocate R&D that reduce cost of producing domestic fuels.
- **Spill-over** across firms (and regions) with one period (decade) lag makes R&D choice static.
- With *ad-valorem* taxes, the firm's objective: minimize cost of supplying energy services $E_{i,t}$

$$\min_{\{e_{k,i,t}\}_1^n, \{p_{k,i,t}\}_2^n} \sum_{k=1}^{n} (1+\tau_{k,i,t})\, p_{k,i,t} e_{k,i,t}$$
$$- P_{i,t} \left(\mathcal{E} \left(e_{1,i,t}, \ldots, e_{n,i,t} \right) - E_{i,t} \right) - \Lambda_{i,t} RD_{i,t} \left(p_{2,i,t}, \ldots, p_{n,i,t} \right).$$

- First order condition for R&D cost reduction,

$$(1+\tau_{k,i,t})\, e^*_{k,i,t} = \Lambda_{i,t} \frac{\partial RD_{i,t} \left(p_{2,i,t}, \ldots, p_{n,i,t} \right)}{\partial p_{k,i,t}}.$$

- FOC with *per unit* taxes

$$e^*_{k,i,t} = \Lambda_{i,t} \frac{\partial RD_{i,t} \left(p_{2,i,t}, \ldots, p_{n,i,t} \right)}{\partial p_{k,i,t}}.$$

R&D constraint specification

- As a starter, repr energy firm reduce domestic costs (not oil) subject to a constraint on a weighted sum log cost reductions over benchmark costs (given from previous periods aggregate global or regional R&D).
- With two domestic energy sources R&D constraint is

$$RD_{i,t}\left(p_{2,i,t}, p_{3,i,t}\right) \equiv \varepsilon_{2,i} \ln \frac{p_{2,i,t}}{\bar{p}_{2,i,t-1}} + \varepsilon_{3,i} \ln \frac{p_{3,i,t}}{\bar{p}_{3,i,t-1}} + a \geq 0$$

- Also constraint that $p_{k,i,t} \leq \bar{p}_{k,i,t-1}$, later to return to. E.g., cannot reduce cost of green by increasing cost of coal over benchmark.
- FOC condition for R&D choice with *ad-valorem* taxes

$$\left(1 + \tau_{k,i,t}\right) e^{*}_{k,i,t} = \varepsilon_{k,i} \frac{\Lambda_{i,t}}{p_{k,i,t}}$$

- Note that direct effect of taxes is to *increase* marginal value of cost reductions (LHS). Also indirect effect in opposite direction. Higher taxes reduce use $\left(e^{*}_{k,i,t}\right)$ and thus reduce value of reducing costs.

No effect of taxes on after tax costs and use!

- Using expression for optimal supply $e^*_{k,i,t}$ (same as before) in $\left(1+\tau_{k,i,t}\right) e^*_{k,i,t} = \frac{\Lambda_{i,t}}{p_{k,i,t}}$ yields

$$\frac{\left(1+\tau_{2,i,t}\right) p^*_{2,i,t}}{\left(1+\tau_{3,i,t}\right) p^*_{3,i,t}} = \left(\frac{\varepsilon_2}{\varepsilon_3}\right)^{\frac{\rho-1}{\rho}} \left(\frac{\lambda_2}{\lambda_3}\right)^{\frac{1}{\rho}}, \text{ and}$$

$$\frac{e^*_{2,i,t}}{e^*_{3,i,t}} = \left(\frac{\lambda_3}{\lambda_2}\frac{\varepsilon_2}{\varepsilon_3}\right)^{\frac{1}{\rho}}$$

- **R&D completely undo taxes!** (When FOC is satisfied). Intuition, the two effects discussed above cancel each other. Note that this is independent of ρ!

Per unit tax

- If tax is per unit, no longer closed-form solution.

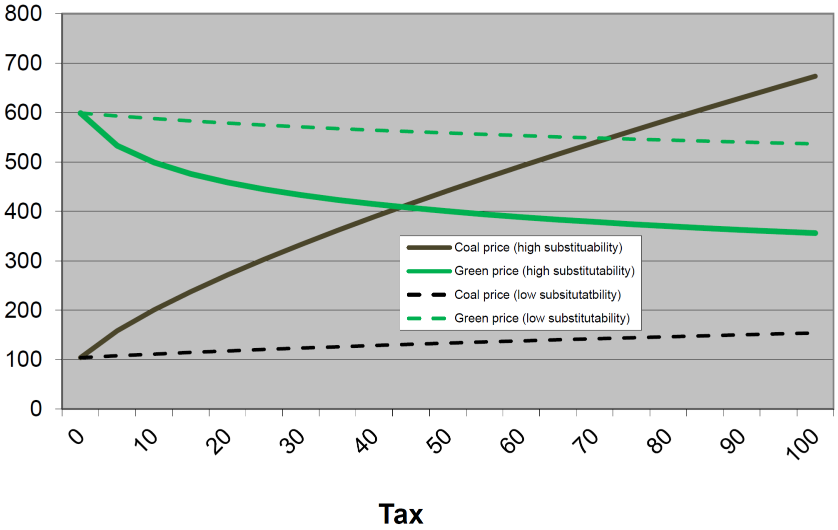
$$\frac{p_{2,i,t}\left(\tau_{2,i,t}+p_{2,i,t}\right)^{\frac{1}{\rho-1}}}{p_{3,i,t}\left(\tau_{3,i,t}+p_{3,i,t}\right)^{\frac{1}{\rho-1}}}=\frac{\varepsilon_2}{\varepsilon_3}\left(\frac{\lambda_2}{\lambda_3}\right)^{\frac{1}{\rho-1}}$$

- Higher taxes, reduce use and thus reduce value of reducing costs. Effect in other direction (that lower price also reduce tax spending) absent.
- Strong effects if subst elasticity σ is close to unity (direction of R&D highly sensitive to taxes)

$$\left.\frac{dp_{2,i,t}}{d\tau_{2,i,t}}\right|_{\tau_{3,i,t}=\tau_{2,i,t}=0}=\frac{\sigma}{1-\sigma}\varepsilon_3.$$

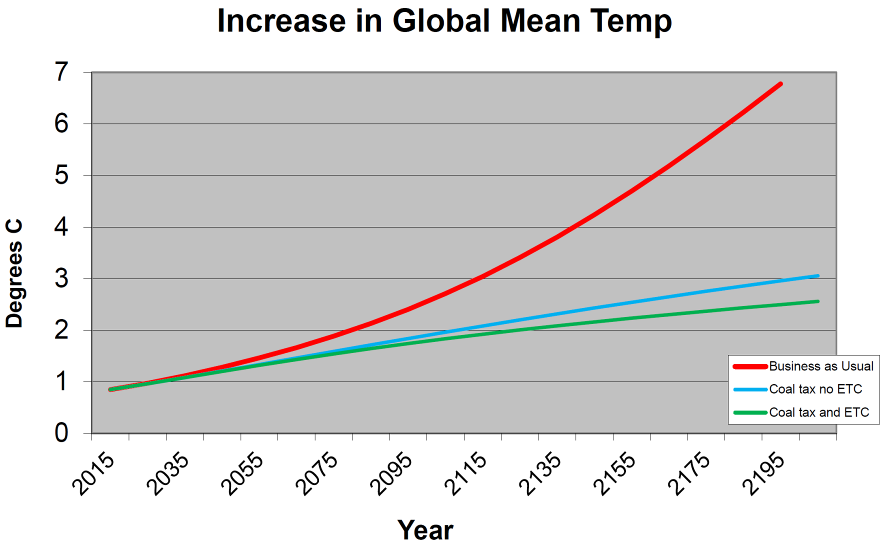
- Use previous calibration for Europe and assume interior solution for R&D with improvements in both green and coal implies $\varepsilon_3=0.778$ and $\varepsilon_2=0.222$ (more difficult to reduce cost of green).

Coal and Green energy prices in interior R&D optimum



Is solution interior?

- Until now, assumed R&D FOC is satisfied. Is it?
  1. Not if elasticity of substitution between energy sources >1.
  2. Not if corner $p_{k,i,t} \leq \bar{p}_{k,i,t-1}$ binds – then at corner for a number of periods. Zero R&D resources spent on energy source k.
- Corner calibration: if no R&D efforts is spent on coal, the relative price of coal increases by 2% (GDP-growth) per year.
- Then from RD-constraint price of green $p_{2,i,t}$ falls, by $\frac{\varepsilon_2}{\varepsilon_3} * 2\% = 0.56\%$ per year. Conversely, if all R&D is spent on coal, relative price of coal falls by 7.2% per year.
- Optimal carbon tax implies a corner! All R&D on green energy - stagnant coal production technology. -> 2% yearly increases in coal prices and 0.56% reductions in green.
- Would result also with taxes much smaller than "optimal"!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Year
Business as Usual
Coal tax no ETC
Coal tax and ETC

Conclusion

- Model: decentralized model with potentially high resolution, many sources of energy and endogenous technical change yet simple and transparent.
- Policy:
  1. Carbon taxes are effective – also if lower than optimal, but they need to have broad coverage.
  2. Taxes on conventional oil/gas irrelevant for the climate.
  3. Important that coal prices increase over time – technical change there must stop.
  4. With non-conventional oil/gas in elastic supply, taxes on these important.
  5. Carbon taxes reduce incentive to improve extraction technology only if they are additive.