CLIMATE POLICY:
A SECOND-BEST PERSPECTIVE

KEYNOTE LECTURE
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Price carbon consumption

- Via a global carbon tax or national carbon taxes with border tax adjustments.
- Or emissions trading scheme if done globally.
- Europe's policies are a failure: carbon production is priced and has gone down but carbon consumption including imports from China etc is not and has gone up. And it might be due to deindustrialisation rather than pricing carbon.
- Europe has focused instead on second-best subsidies for wind and solar energy, 'picking winners', and grandfathering emission rights.

How does carbon pricing work?

- Curbs demand for fossil fuel: less car trips, heating a degree less, etc.
- Induces substitution away from fossil fuel to renewables and brings forward the carbon-free era.
- Encourages learning by doing and R&D into clean fuel alternatives and energy-saving technology.
- Encourages to leave more fossil fuel in the crust of the earth.
- *Induces substitution from tar sands, coal, crude oil to less carbon-intensive gas.*
- *Encourages CCS and limits slash & burn of forests.*

Set price to social cost of carbon (SCC)

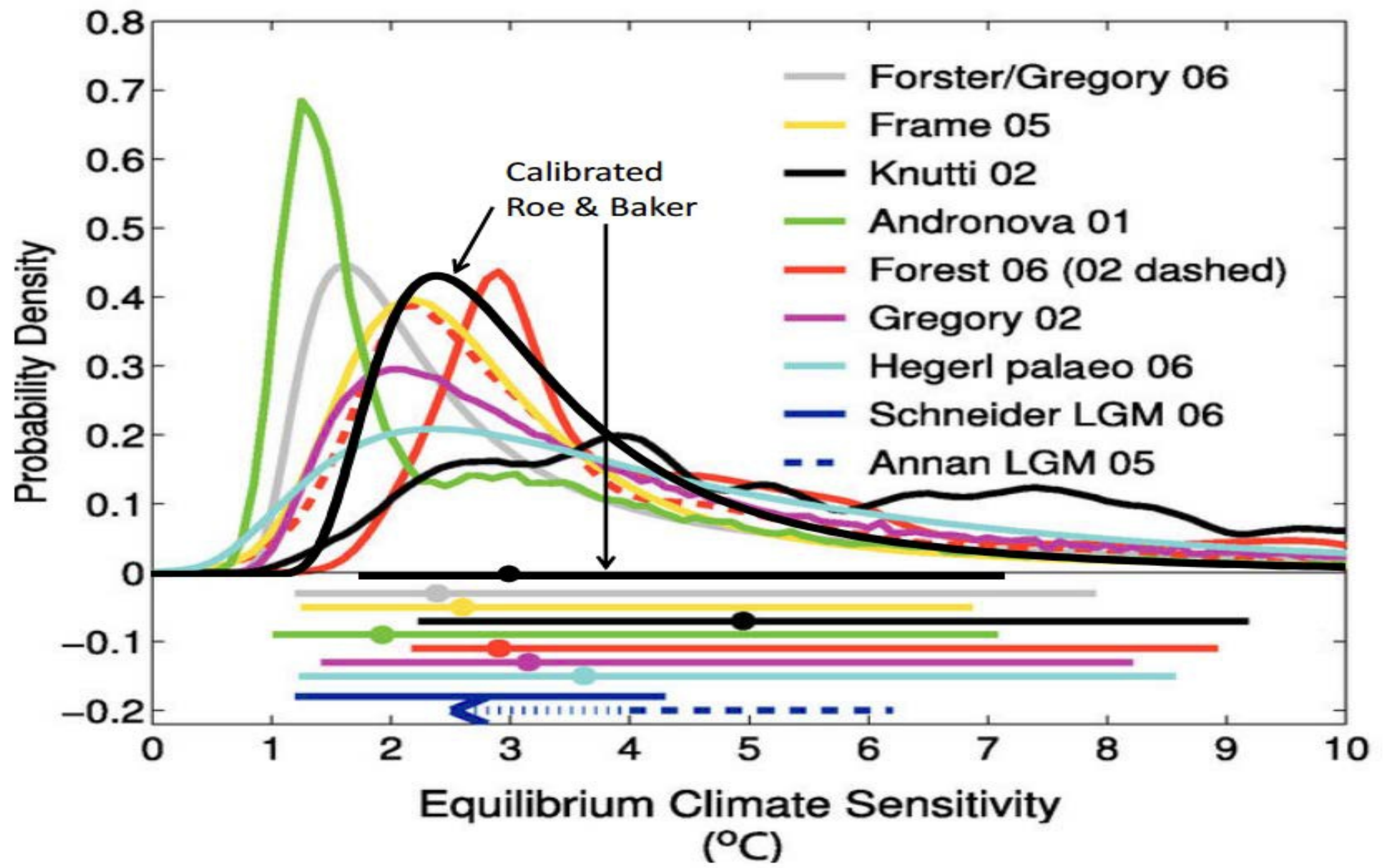
- SCC is present discounted value of all future marginal production damages of emitting one extra ton of carbon today.
- SCC is highly sensitive to the social rate of discount: Nordhaus versus Stern.
- SCC is higher for rich than for poor countries … if there are no international transfers.
- We derive a simple rule for the SCC.

US Interagency Working Group (2010)

SCC 2010 – 2050 (2007 dollars)

Discount Rate	5%	3%	2.5%
Year	Avg	Avg	Avg
2010	17	**78**	129
2015	21	87	141
2020	25	96	153
2025	30	108	168
2030	36	120	183
2035	41	132	199
2040	47	143	214
2045	52	154	226
2050	58	164	238

Estimates of the *ECS* = ω

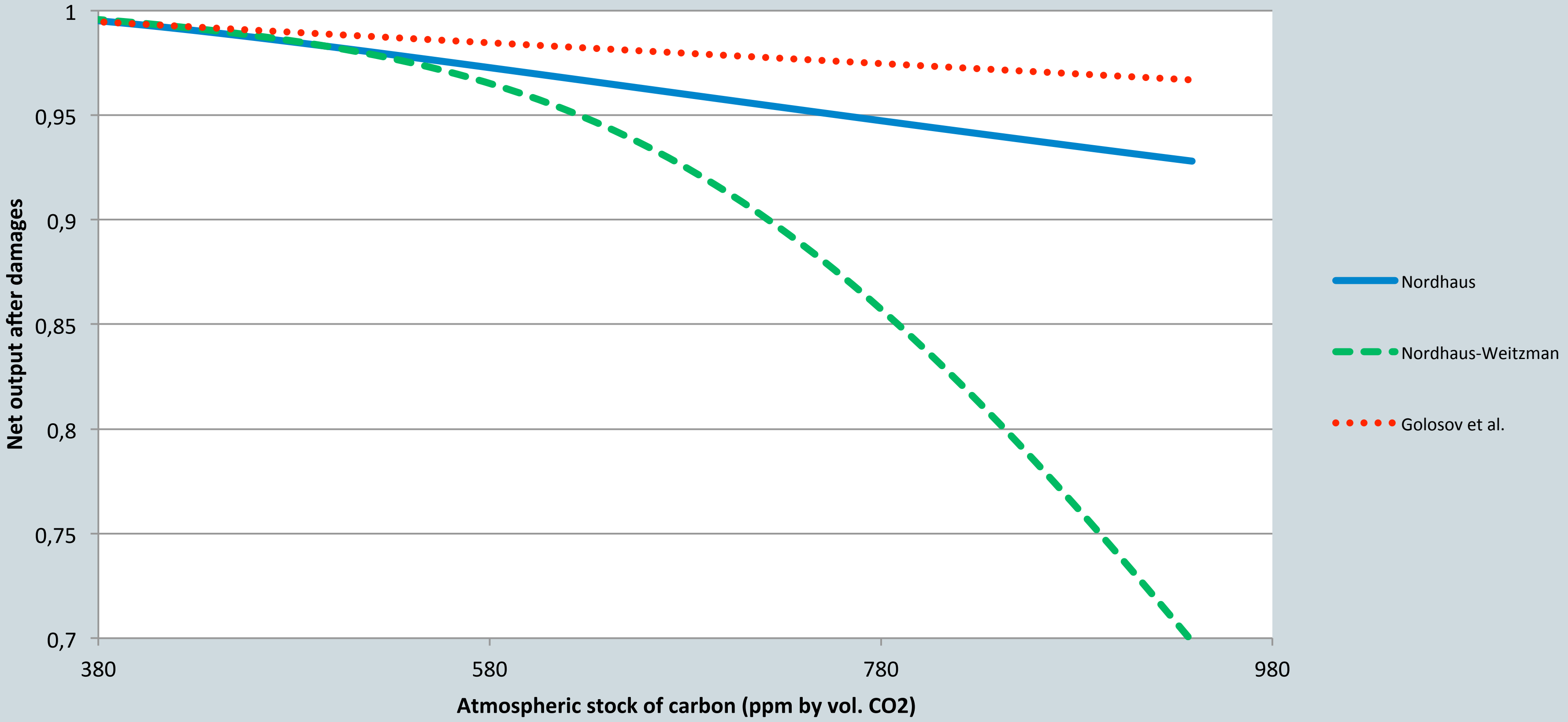


Carbon cycle supposes:

- Equilibrium climate sensitivity ω is set to 3 in line with IPCC (2007). Has been revised downwards.
- 20% of carbon emissions stays up in the atmosphere and remaining part has mean lifetime of 300 years.
- Parameter φ_0 is calibrated so that about half of the carbon impulse is removed after thirty years.
- Time lag of about 40 years between peak temperature and emissions (cf. Gerlagh and Liski, 2016).
- Ignores positive feedback and catastrophes: e.g., release of carbon from the ocean floors at higher temperatures.

What's left of output after damages from warming?

Perhaps, damages more convex than in Nordhaus!



Global warming damages: what is left?

- Nordhaus' RICE (2007): $Z(T) = \dfrac{1}{1 + 0.00284T^2} = \dfrac{1}{1 + (T/18.8)^2}.$
- Golosov et al. (2013): $Z(E_t) \cong \exp\left[-2.379 \times 10^{-5}(2.13E_t - 581)\right].$
- These two fairly flat. We use latter in our simple rule.

- Nordhaus-Weitzman based on Ackerman & Stanton (2012) is more realistic for higher temperatures:

$$Z(T) = \frac{1}{1 + (T/20.2)^2 + (T/6.08)^{6.76}}.$$

- We use this in our full optimising IAM too.

Second best

Decentralisation theorem fails if not enough instruments:

- Simple rules
- Renewable subsidy, but for political reasons no carbon taxes. Or postponing carbon taxes. Leads to Green Paradox (Sinn; Kalkuhl, Lessmand and Edenhofer, 2013, REE).
- Non-Kyoto countries do not participate, so carbon leakage.
- National adaptation investments instead of global mitigation.

Also fails with:

- Hyperbolic discounting (Gerlagh and Liski, 2016; Belfiori, 2015; Iverson and Karp, 2016).
- Overlapping generations and no intergenerational bequest motive.
- Distorting taxes due to unavailability of individualised lump-sum tax (cf. ‘double dividend’ literature, but now Kaplow & Jacobs and de Mooij, 2015, JEEM).
- Asymmetric information and other uncorrected market failures.

ASSUMPTIONS TO GET SIMPLE RULE FOR SCC

(Rezai and van der Ploeg, 2016, JAERE)

- Ramsey growth dynamics converges much faster than carbon cycle dynamics: use trend rate of economic growth *g*
- A fifth of emissions stays up in atmosphere forever and of rest 60% is absorbed by oceans and earth surface within a year and remainder decays at rate of 1/300 years. After 3 decades half has left the atmosphere, so after *t* years $LEFT_t = 0.2 + 0.4 \times 0.8 \times (1\text{-}0.0023)^{t-1}$ is left of 1 tC emitted today.
- Damages are 2.38% of global GDP per trillion ton of extra carbon in atmosphere, so damage of one ton emitted today after *t* years is $0.0238 \times GDP_t \times LEFT_t$. Approximates damages from RICE well (cf. 3 slides back).
- Average time it takes between an increase in carbon and increase in global mean temperature: 40 years.

SIMPLE RULE FOR SCC

$$SCC = \left(\left[\frac{0.2}{r} + \frac{0.32}{r + 0.0023} \right] \times 0.0238 \times GDP \right) \times \left(\frac{1}{1 + r \times 40} \right),$$

where the rate of discount to discount damages follows from the Keynes-Ramsey rule: $r = \rho + (IIA - 1) \times g.$

- Lower weight to future generations (higher ρ), bigger intergenerational inequality aversion (higher IIA), and richer future generations (higher g) curb desire to make sacrifices to cut future global warming and thus lead to higher carbon price.
- Temperature lag depresses SCC.
- Since climate damages are proportional to world GDP, the global carbon tax is proportional to world GDP too.

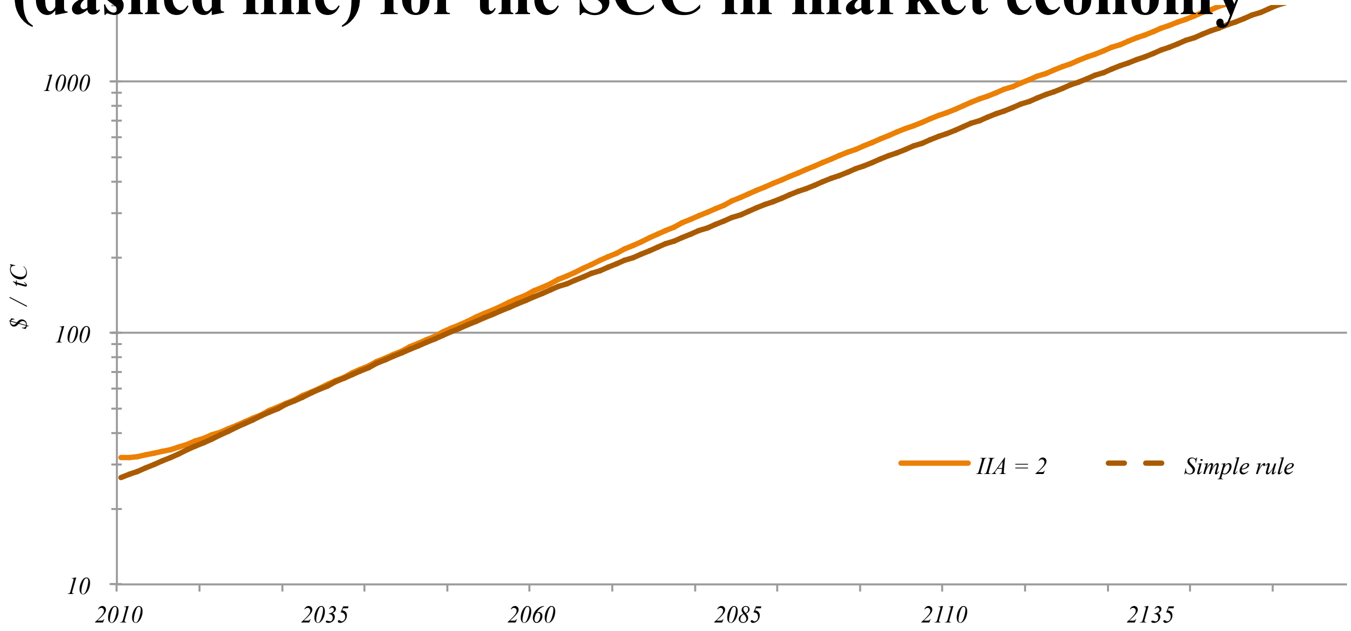
Special case: Golosov et al. (2014, Ectra)

- *IIA* = 1 and no temperature lag: $SCC = \left[\frac{0.2}{\rho} + \frac{0.32}{\rho + 0.0023} \right] \times 0.0238 \times GDP$
- Formula is *exact* under Brock-Mirman assumptions: Cobb-Douglas production, 100% depreciation each period, and extraction requiring no capital.
- Also based on seminal contribution of Nordhaus (1991, EJ).
- A lower discount rate ρ pushes up the SCC.
- A bigger proportion of atmospheric carbon that stays up for ever in atmosphere pushes up SCC.
- Faster decay of the other part depresses SCC.
- SCC/GDP is independent of technology and depreciation rate!
- Van den Bijgaart et al. (2016, JEEM) also study simple rules, but also do not test them in second-best setting.

Back-on-the-envelope calculations

- Let g = 2%, IIA = 2 and ρ = 0. World GDP 2014 = 76 T$. Hence, SCC is 55 $/tC = 15 $/tCO2 or 13 cents/gallon petrol, and rises subsequently at 2%/year.
- Higher discount rate, ρ = 2%, cuts the SCC to 20 $/tC.
- Doubling IIA to 4 cuts SCC of 10 $/tC.
- Pessimistic trend growth of g = 1% boosts SCC to 132$/tC which then grows in line with global GDP at mere 1%/year.
- Golosov et al. (2014): IIA = 1, ρ = 1.4% gives SCC of 81 $/tC.
- Can allow for damages to trend growth rate (Dell, et al., 2012, AEJ: Macro). This pushes up the SCC a lot. Curbs carbon budget to 452 GtC & max. warming to 2.3C.
- Simple rules perform very well in full optimising IAM.

Test true optimum (solid line) versus simple rule (dashed line) for the SCC in market economy



		Fossil fuel Only	Renewable Only	Carbon used	maximum temperature	Welfare loss
IIA=2	First best	2010-2060	2061 –	955 GtC	3.1 °C	0%
	Business as usual	2010-2078	2079 –	1640 GtC	4.0 °C	- 3%
	Simple rule	2010-2061	2062 –	960 GtC	3.1 °C	- 0.001%

Simple rule: more general damages

- If elasticity of marginal climate damages w.r.t. world GDP is ε, we get:

$$SCC_t \cong \left(\frac{0.2}{\rho + (IIA - \varepsilon)g} + \frac{0.32}{\rho + (IIA - \varepsilon)g + 0.0023} \right) \times \left(1 + 40 \times \left[\rho + (IIA - \varepsilon)g\right]\right)^{-1} \times 0.0238 \times GDP_t^{\varepsilon} GDP_0^{1-\varepsilon}.$$

- Additive damages ($\varepsilon = 0$) leads to a much lower SCC with a much bigger carbon budget of 1600 GtC. Substitutability of damages matters!
- Dell et al. (2012, *AEJ: Macro*) estimates effect of 1° C on poor and rich countries growth rate is -1.171pp and -0.152pp, resp. Moore and Diaz (2015, NCC) confirm that this pushes up optimal SCC by several factors.

Better stories for the discount rate and the rule?

- Quasi-hyperbolic discounting (Laibson, 1997): more impatient today than in future. This depresses the SCC. Need to do this in a market economy for SPNE against one self (Gerlagh and Liski, 2016; Iverson and Karp, 2016).
- Procrastination with generalised hyperbolic discounting or political economy with partisan bias and ongoing regime switches (van der Ploeg and Schmitt, 2016).
- Gamma discounting and dismal theorem (Weitzman).
- Policy makers discount future less than private agents, so subsidise sequestration at the SCC and price gross emissions (net of CSS) at a higher rate (Belfiori, 2016).
- Uncertainty about TFP or ECS and prudence lowers the discount rate and pushes up the SCC (Gollier, Traeger).
- Also for multiple interacting risks of climate tipping if there is no Jehova Witness World (Lemoine and Traeger, Cai et al., NCC, 2016).

Agenda: design simple rules for policy makers and test them in second-best settings

- Quasi-hyperbolic discounting with discount factors 1, $\beta\delta$, $\beta\delta^2$, $\beta\delta^3$, … and $0 < \beta < 1$ leads to a simple modification of the simple rule.
- Generalised hyperbolic discounting with discount factors (in continuous time) $(1 + a)^{-\rho/a}$ which gives exponential discounting $\exp(-\rho t)$ as $a \rightarrow 0$. Rule less easy to adjust, but could try to fit SCC/GDP from lots of true optimal runs to some specified decaying function of time and see how good it fits.
- Convex damages (Ackerman and Stanton), so fit a rule for SCC/GDP to lots of true optimisation runs as increasing function of temperature (or the carbon stock). This gives, like the Taylor rule for the nominal interest rate, a simple two parameter rule.

Also simple rules for stranded assets and energy transition

- At time of energy transition scarcity rent is zero.
- More carbon assets are stranded if net cost of renewable energy is low and price of carbon is high:

$$G\left(S(T)\right) + SCC(T) = b(T) - \theta^{B}(T) < b(T) \quad \Rightarrow$$

$$S(T) = G^{-1}\left(b(T) - \theta^{B}(T) - SCC(T)\right)$$

- Can also derive simple rule for optimal time of phasing out fossil fuel. This also occurs more quickly if SCC is high and renewable energy cost is low.

ABANDONING FOSSIL FUEL: HOW MUCH AND HOW FAST (Rezai and van der Ploeg, 2016)

- Derive first-best optimal global carbon price and renewable subsidy from green Ramsey growth IAM with exhaustible fossil fuel and learning by doing in renewable use.
- How fast to abandon fossil fuel and when to switch to renewable energy and the carbon-free economy?
- How much fossil fuel to leave stranded?
- How do *second-best* climate policies fare when pricing carbon is infeasible and one has to rely on renewable subsidy only? How much does commitment help to mitigate Green Paradox effects?

Features of our optimising IAM

- Fossil fuel extraction cost rises as less reserves are left, which gives rise to untapped fossil fuel.
- Price of fossil fuel consists of this cost, the scarcity rent and SCC.
- Renewable energy gets cheaper as more is used. This gives rise to an intermediate phase where renewable and fossil fuel energy are used together.
- Price of renewable energy corresponds to this cost minus any learning-by-doing subsidy.
- Temporary population boom and ongoing technical progress.

Preview of punch lines

- First best: aggressive renewable subsidy to bring renewable energy quickly into use and gradually rising carbon tax to price and phase out fossil fuel energy. 'Third Way' to climate policy.
- Crucial to lock up substantial part of carbon assets.
- Relationship between the optimal carbon price and GDP is hump-shaped, but not so different from linear.
- Second-best subsidy without a carbon price induces Green Paradox effects, but works much better if policy makers can commit to announced future policies!

Green Ramsey IAM

Utilitarian welfare with η = EIS = 1/IIA:

$$\sum_{t=0}^{\infty}(1+\rho)^{-t}L_t U_t(C_t/L_t)=\sum_{t=0}^{\infty}(1+\rho)^{-t}L_t\left[\frac{(C_t/L_t)^{1-1/\eta}-1}{1-1/\eta}\right] \text{ subject to}$$

$$K_{t+1}=(1-\delta)K_t+Z(T_t)H(K_t,L_t,F_t+R_t)-G(S_t)F_t-b(B_t)R_t-C_t,$$

$$B_{t+1}=B_t+R_t,\quad B_0=0,$$

and linear model of the carbon cycle on next slide.

Simple linear model of carbon cycle

Golosov et al. (2014). No modelling of lower & bottom oceans. No positive feedback.

$$E_{t+1}^{P} = E_t^{P} + \varphi_L F_t, \quad \varphi_L = 0.2, \quad E_0^{P} = 103 \text{ GtC}$$

$$E_{t+1}^{T} = (1-\varphi)E_t^{T} + \varphi_0(1-\varphi_L)F_t, \quad \varphi = 0.0228,$$

$$\varphi_0 = 0.393, \quad E_0^{T} = 699 \text{ GtC}$$

$$S_{t+1} = S_t - F_t, \quad S_0 = 4000 \text{ GtC}$$

$$T_t = \omega \ln\left(E_t / 280\right) / \ln(2), \omega = 3, \quad E_t \equiv (E_t^{P} + E_t^{T}) / 2.13 \text{ ppmv CO2}$$

Efficiency conditions

- Keynes-Ramsey rule (Euler equation):

$$\frac{C_{t+1}/L_{t+1}}{C_t/L_t}=\left(\frac{1+r_{t+1}}{1+\rho}\right)^{\eta}, \quad r_{t+1}\equiv Z_{t+1}H_{K_{t+1}}-\delta.$$

- Fossil fuel and renewable use:

$$Z_t H_{F_t+R_t}\leq G(S_t)+\theta_t^S+\theta_t^E, \quad F_t\geq 0, \quad \text{c.s.,}$$

$$Z_t H_{F_t+R_t}\leq b(B_t)-\theta_t^B, \quad R_t\geq 0, \quad \text{c.s.}$$

- Dynamics of the scarcity rent (Hotelling rule):

$$\theta_{t+1}^S=(1+r_{t+1})\theta_t^S+G'(S_{t+1})F_{t+1} \quad \Rightarrow \quad \theta_t^S=-\sum_{s=0}^{\infty}\left[G'(S_{t+1+s})F_{t+1+s}\Delta_{t+s}\right].$$

Efficiency conditions (continued)

- Compound discount factors: $\Delta_{t+s} \equiv \prod_{s'=0}^{s}(1+r_{t+1+s'})^{-1}, s \geq 0.$
- Dynamics of social benefit of learning by doing:

$$\theta^{B}_{t+1} = (1+r_{t+1})\theta^{B}_{t} + b'(B_{t+1})R_{t+1} \quad \Rightarrow \quad \theta^{B}_{t} = -\sum_{s=0}^{\infty}\left[b'(B_{t+1+s})R_{t+1+s}\Delta_{t+s}\right].$$

- Dynamics of the social cost of carbon (SCC):

$$\theta^{PE}_{t+1} = (1+r_{t+1})\theta^{PE}_{t} + Z'(E^{P}_{t+1} + E^{T}_{t+1})H_{t+1},$$

$$(1-\varphi)\theta^{TE}_{t+1} = (1+r_{t+1})\theta^{TE}_{t} + Z'(E^{P}_{t+1} + E^{T}_{t+1})H_{t+1} \quad \Rightarrow$$

$$\theta^{E}_{t} = -\sum_{s=0}^{\infty}\left[\left\{\varphi_L + \varphi_0(1-\varphi_L)(1-\varphi)^{s}\right\}\Delta_{t+s}Z'(E^{P}_{t+1+s} + E^{P}_{t+1+s})H_{t+1+s}\right].$$

Calibration

- EIS =η = 0.5, IIA = 2, ρ = 10%/decade = 0.96%/year
- $G(S)$ = 0.35 S_0/S , where 0.35 follows from fossil fuel production costs being 5-7% share of initial energy in GDP (350 \$/tC or 35\$/barrel of oil). Hence, extraction costs quadruple if another 2000 GtC is extracted.
- K_0 = 200 T\$, δ = 50%/decade = 6.7%/year.
- $L(t)$ = 8.6 - 2.98 exp(-0.35t), so population is 6.5 billion in 2010, grows initially at 1%/year and flattens off at plateau of 8.6 billion.
- A_t^L = 3 – 2.443 exp(-0.2t), so starts at 2%/year and flattens off at 3 times initial level.

Calibration continued

- Production function with $\alpha = 0.35$, $\beta = 0.06$, and $\vartheta = 0$ (Leontief) or 0.5 (CES):

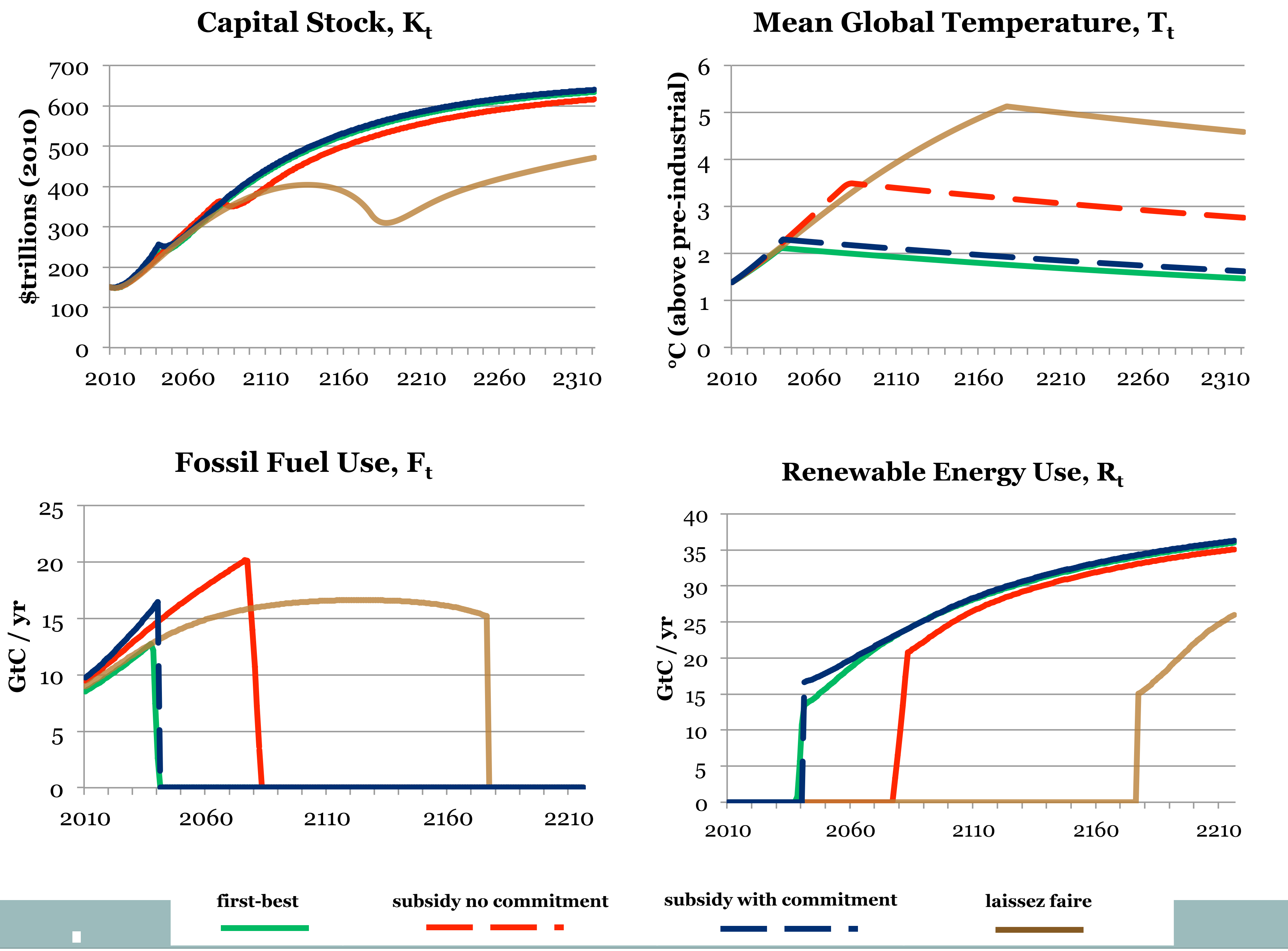
$$H_t = H_0 \left[(1-\beta) \left(\frac{AK_t^{\alpha} (A_t^L L_t)^{1-\alpha}}{H_0} \right)^{1-1/\vartheta} + \beta \left(\frac{F_t + R_t}{\sigma H_0} \right)^{1-1/\vartheta} \right]^{\frac{1}{1-1/\vartheta}}.$$

- 2010 GDP = 63 T\$ gives $A = 34.67$.
- With Leontief 2010 carbon input is $F_0 = \sigma Z_0 H_0 = 8.36$ GtC, which gives $\sigma = 8.36/(2.13 \times 63) = 0.062$.

- Let $b(B_t) = \chi_1 + \chi_2 \exp(-\chi_3 B_t)$ as cost of producing with only carbon-free energy is $\sigma b(0) = 5.6\%$ plus cost of conventional energy is 6.4% = 12% so $b(0) = 0.12/0.062 = 2 = \chi_1 + \chi_2$. Thru' learning by doing this cost can be reduced by 60% to a lower limit of 5% of GDP, so we set $b(\infty) = \chi_2 = 0.6 \times 2 = 1.2$. Cost of energy drops by 20% in a decade if all energy is renewable, so we set $\chi_3 = 0.008$.

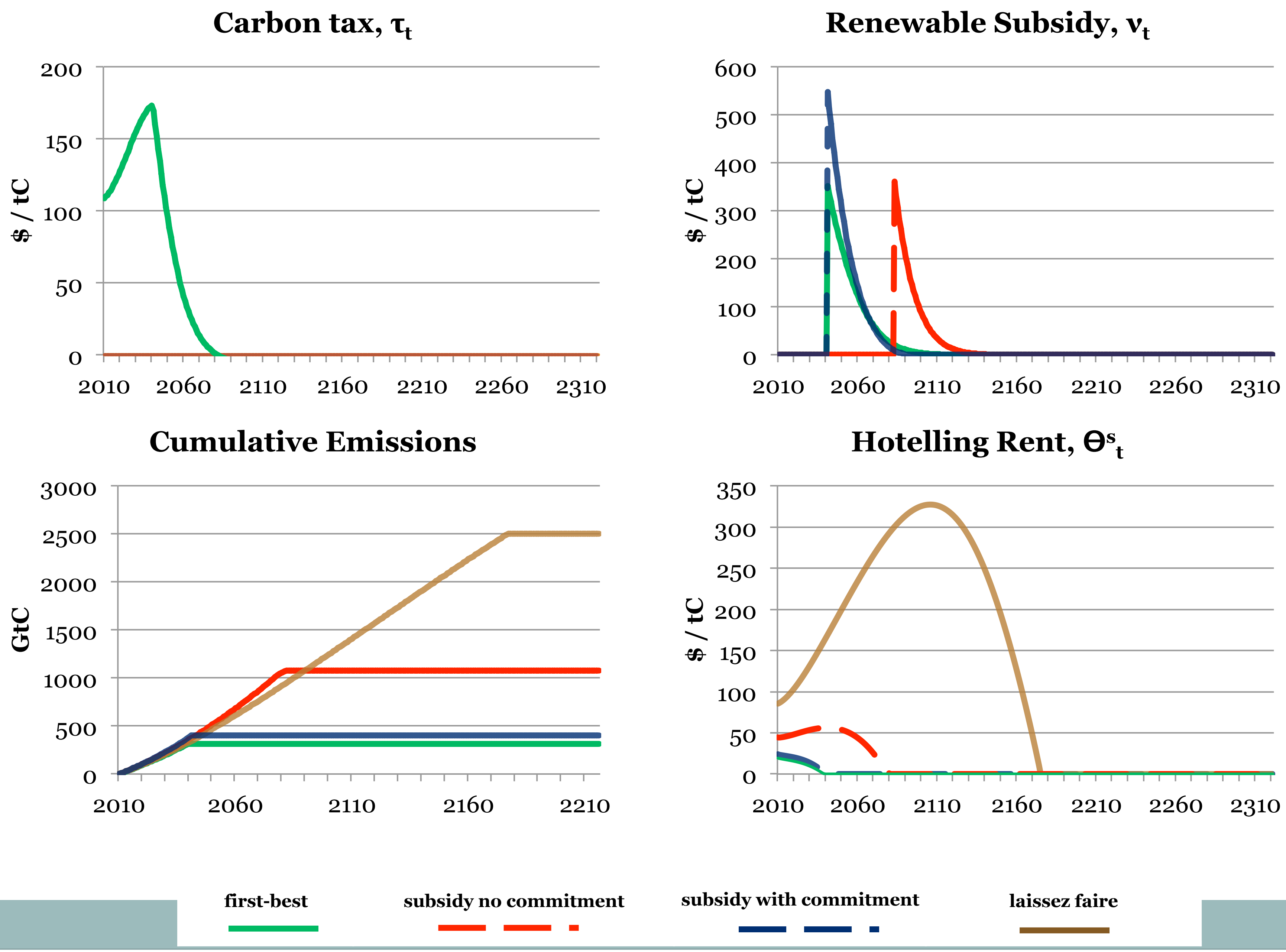
Policy simulations

- Solution decade by decade from 2010 to 2600:
  t = 1 is 2010-2020, .., t = 60 is 2600-2610.
- I. first best where the carbon price = optimal SCC, and the renewable subsidy to the optimal SBL (solid green lines) ━━━
- II. Second-best optimal subsidy
  without commitment (dashed red lines) — — -
- III. Second-best optimal subsidy
  with pre-commitment (dashed blue lines) — — -
- IV. business as usual (BAU) without any policy (solid brown lines) ━━━
- Second best is calculated from decentralised market economy!



Factor substitution and Green Paradox (compare blue and red lines with brown line)

- Technology permits the substitution of energy for capital (e.s. = 0.5 > 0), hence the demand for energy is price-elastic.
- The introduction of a subsidy lowers the benefit of in situ fossil energy (Hotelling rent), lowering its market price.
- More fossil energy is used – the weak Green Paradox effect – but temporary effect on temperature is small. In total, less fossil energy is burnt as subsidy brings forward the end of the fossil fuel era.
- So green welfare might rise (no strong Green Paradox), especially if fossil demand does not and fossil reserves does react strongly to prices.
- With Leontief technology, there is no weak Green Paradox.


Carbon tax, τ_t
$ / tC
200
150
100
50
0
2010
2060
2110
2160
2210
2260
2310
Renewable Subsidy, ν_t
$ / tC
600
500
400
300
200
100
0
2010
2060
2110
2160
2210
2260
2310
Cumulative Emissions
GtC
3000
2500
2000
1500
1000
500
0
2010
2060
2110
2160
2210
Hotelling Rent, Θ^s_t
$ / tC
350
300
250
200
150
100
50
0
2010
2060
2110
2160
2210
2260
2310
first-best
subsidy no commitment
subsidy with commitment
laissez faire

Interpretation

- Optimal policy mix combines persistent carbon tax with aggressive renewable subsidy and cuts warming to 2.1°C.
- Under laissez faire, heating rises to 5.1°C. Missing markets lead to a transitory capital over-accumulation, inducing severe climate damage and a fall in capital stock. Rising extraction costs drive transition.
- If the government can commit to second-best optimal renewable subsidy, it can get close to the first best. There is a weak Green Paradox effect with small increase in temperature.
- If the government cannot commit to the second-best policy, the subsidy is delayed considerably with large Green Paradox effects.

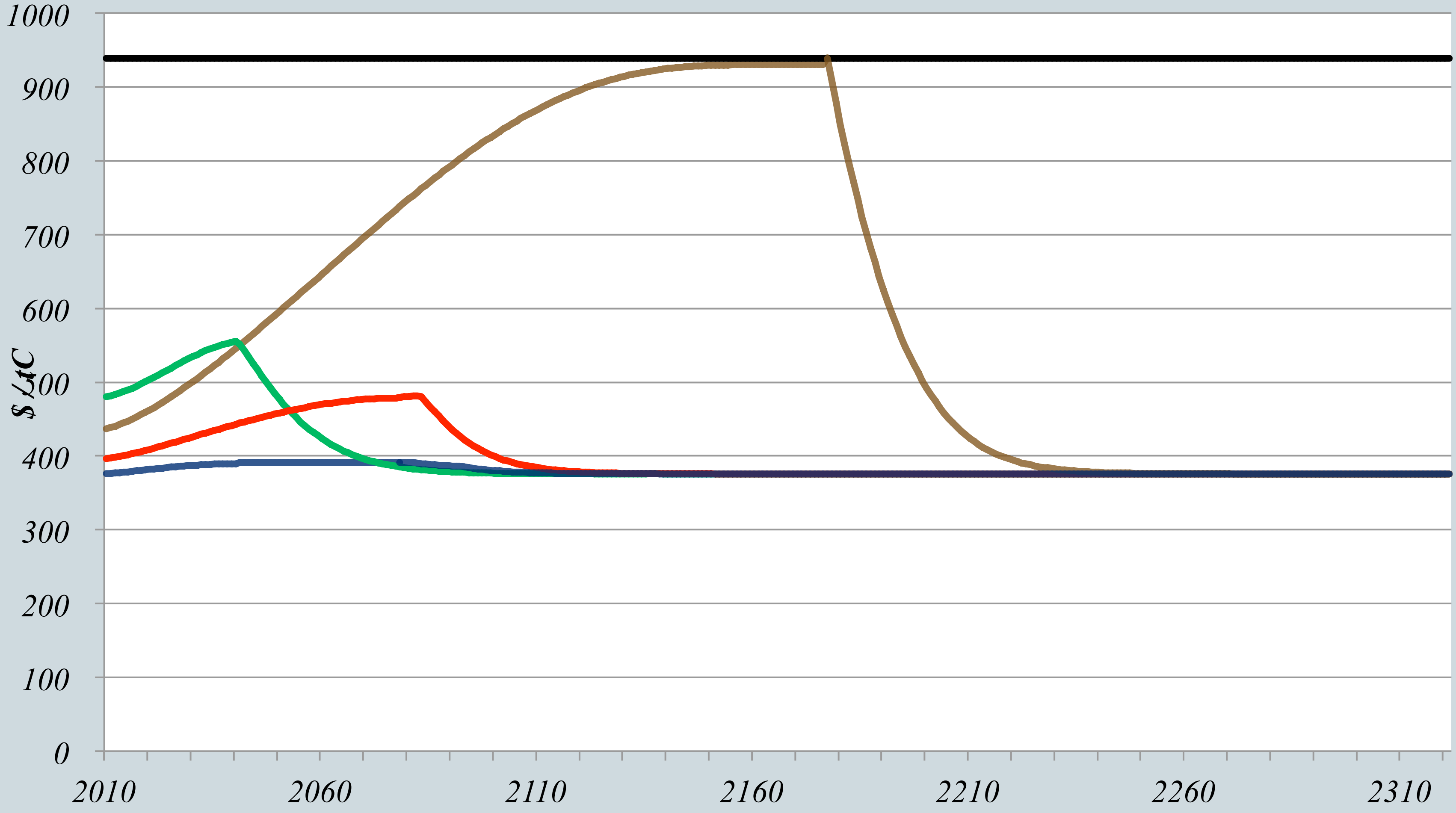
Transition times and carbon budget

	Only fossil fuel	Simultaneous use	Renewable Only	Carbon used
Social optimum	2010-2038	2038-2040	2041 –	320 GtC
SB subsidy (w/o commitment)	2010-2076	2077-2082	2083 –	1080 GtC
SB subsidy (with commitment)	2010-2040	x	2041 –	400 GtC
No policy	2010-2175	x	2175 –	2500 GtC

Welfare losses, SCCs, renewable subsidies and global warming

	Welfare Loss (% of GDP)	Maximum carbon tax τ ($/tC)	Maximum renewable subsidy ($/tC)	max T (°C)
Social optimum	0%	175 $/GtC	350 $/GtC	2.1 °C
SB subsidy (w/o commitment)	-95%		360 $/GtC	3.5 °C
SB subsidy (with commitment)	- 7%		550 $/GtC	2.3 °C
No policy	-598%			5.1 °C

Market price of fossil fuel and renewable ($/tC)



Remarks

- US Interagency Working Group (2010) recommends SCC of 78$/tC rising to 165$/tC in 2050 based on discount rate of 3% per year or of 129$/tC rising to 238$/tC in 2050 based on discount rate of 2.5%. This is in line with our estimates.
- Endogenous total factor and energy productivities would allow for further substitution possibilities between energy and the (K,L)-aggregate in the longer run (see estimates of Hassler et al. (2011)), but tough to calibrate. This would justify more ambitious climate policy.
- Acemoglu et al. (2012) and Mattauch argue for an aggressive subsidy to kick-start green innovation; Nordhaus and Stern Review argue for a rising carbon tax. Our IAM argues for a combination of these policies.

Sensitivity runs: first best and BAU

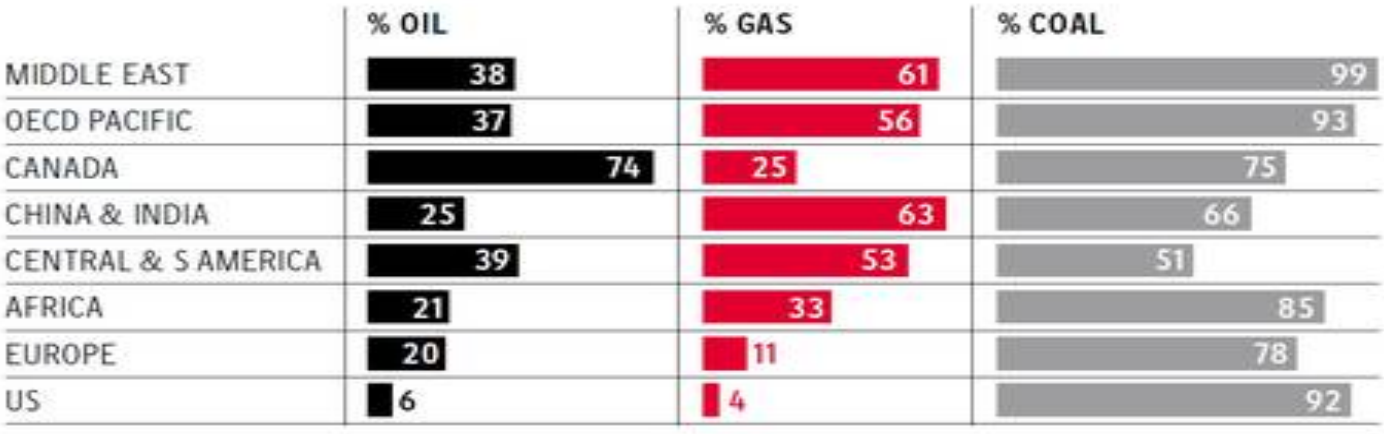
Scenario	First Best				Business as usual		
	Fossil only	Renewable only	Peak warming	Carbon budget	Peak warming	Carbon budget	Welfare loss
Baseline	2010 – 2037	2041 –	2.1°C	316 GtC	5.1°C	2,502 GtC	– 598%
Higher E.S. in production	2010 – 2040	2043 –	2.1°C	304 GtC	5.0°C	2,506 GtC	– 436%
Higher extraction costs	2010 – 2035	2038 –	2.0°C	279 GtC	4.1°C	1,557 GtC	– 259%
Lower growth	2010 – 2039	2044 –	2.1°C	316 GtC	5.1°C	2,501 GtC	– 546%
Higher time preference	2010 – 2063	2067 –	2.8°C	677 GtC	5.1°C	2,506 GtC	– 31%

Sensitivity runs: second best

Scenario	Second Best w. Commitment			Second Best w/o. Commitment		
	Peak warming	Carbon budget	Welfare loss	Peak warming	Carbon budget	Welfare loss
Baseline	2.2°C	345 GtC	− 6.0%	3.5°C	1,080 GtC	− 95%
More elastic energy demand	2.2°C	364 GtC	− 11.4%	3.5°C	1,085 GtC	− 94%
More elastic reserves	2.1°C	310 GtC	− 4.3%	2.8°C	683 GtC	− 35%
Lower economic growth	2.2°C	347 GtC	− 6.8%	3.5°C	1,119 GtC	−105%
Higher time preference	2.9°C	714 GtC	− 2.6%	4.0°C	1,462 GtC	−14%

McGlade and Ekins (2015, *Nature*)

- Globally keep 1/3 of oil (Canada, Arctic), ½ of gas and 4/5 of coal (mainly China, Russia, US) reserves unburnt. Reserves are 3x and resources 10-11x the carbon budget. In Middle East 260 billion barrels of oil that should not be burnt.

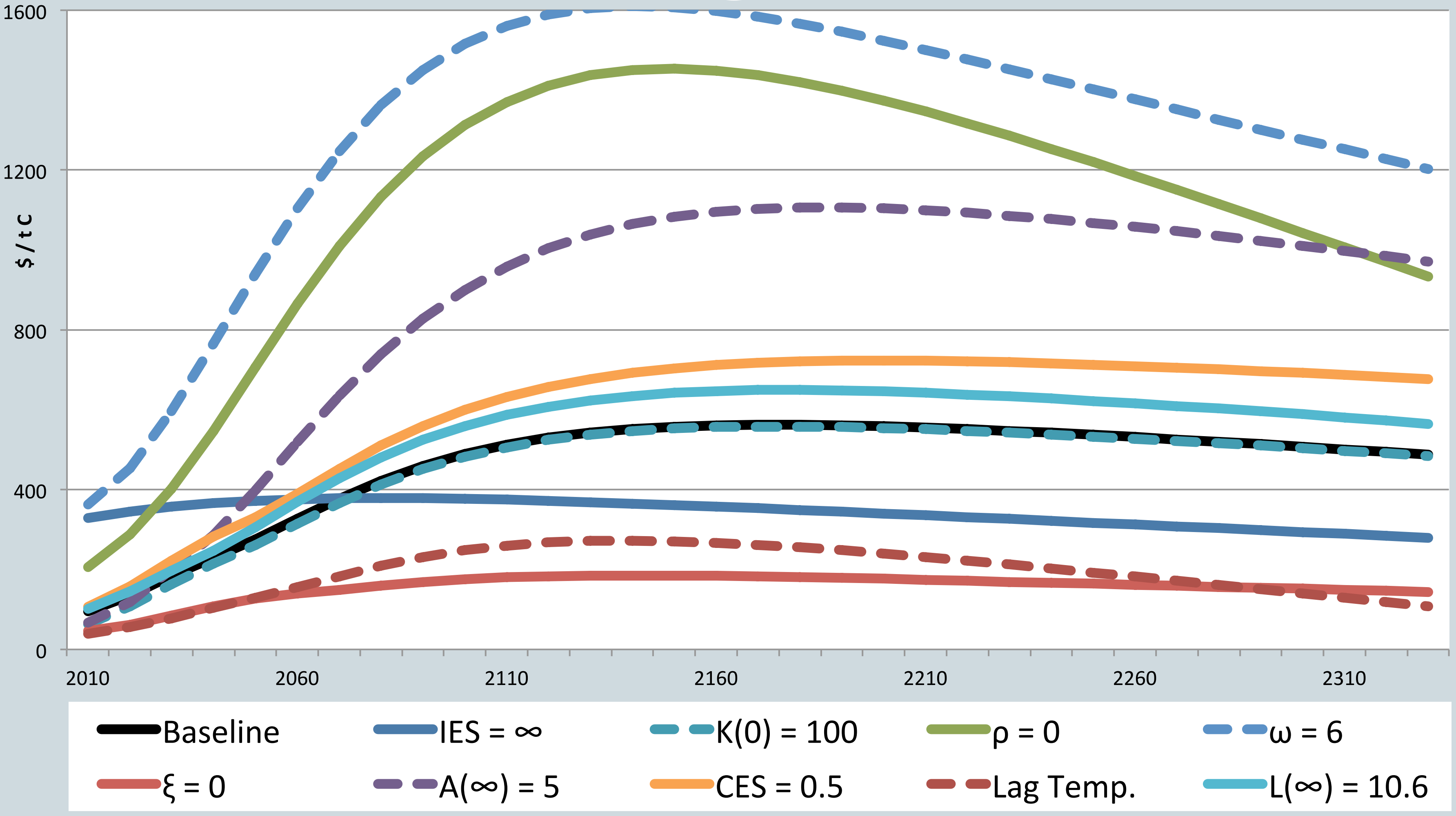


BURN NOTICE WARNING ON ENERGY RESERVES

Regional distribution of reserves to remain unburned in order to avoid exceeding the 2°C "safe" threshold for global warming before the year 2050

SOURCE: UCL

Social Cost of Carbon - Sensitivity



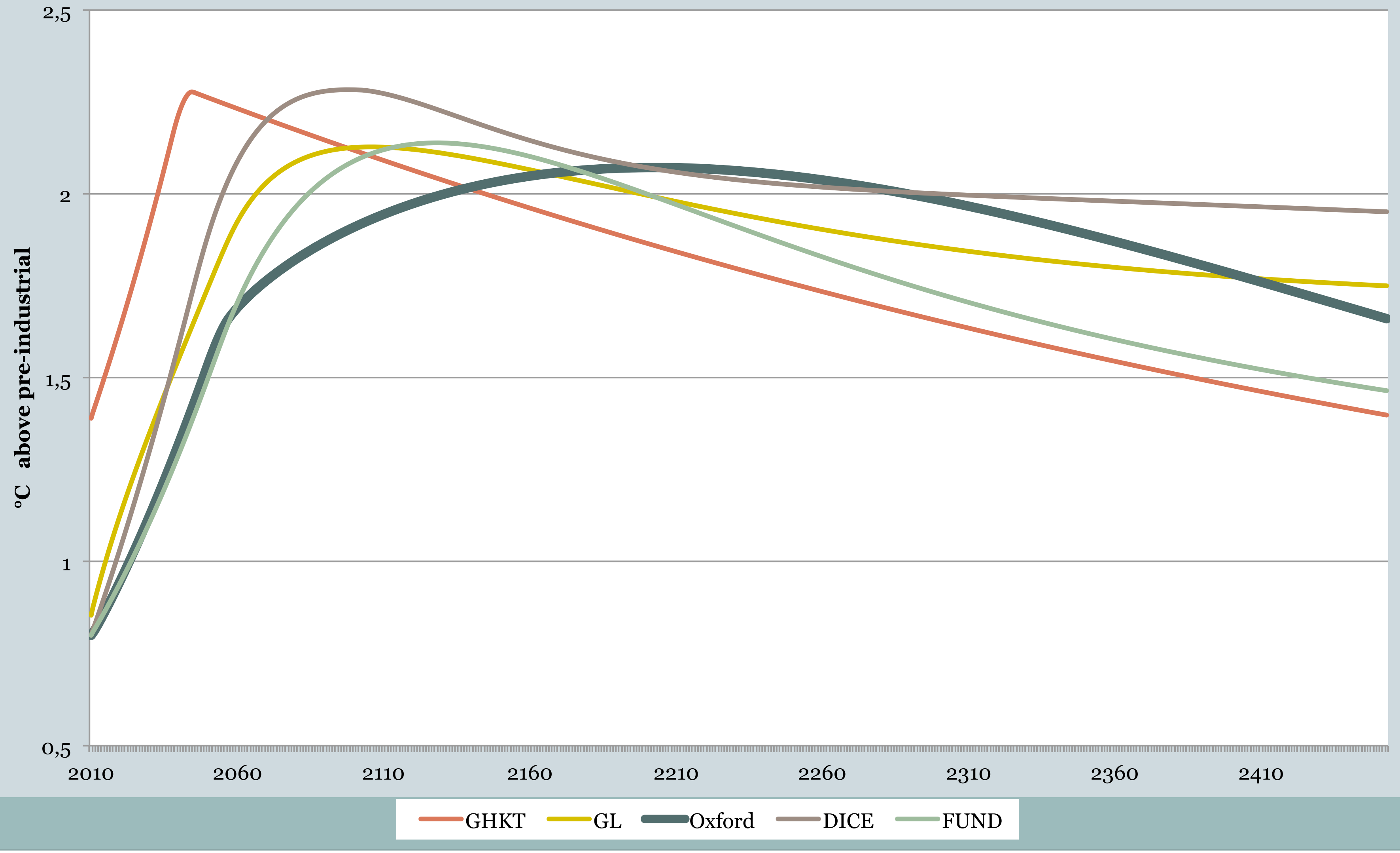
Sensitivity to economic and climate assumptions

- Climate policy is more aggressive with higher carbon tax and renewable subsidy and more fossil fuel stranded if:
  - the equilibrium climate sensitivity ω is higher (6 not 3),
  - the discount rate ρ is lower (0 not 0.96%/year),
  - technological progress is more rapid ($A(\infty) = 5$ not 3),
  - elasticity of factor substitution ϑ is higher (0.5 not 0),
  - population explosion is more substantial ($L(\infty) = 10.6$ not 8.6 billion).
- But climate policy less aggressive if:
  - there is a lag between warming up and higher carbon concentration,
  - intergenerational inequality aversion is weaker,
  - global warming damages are additive ($\xi = 0$), not multiplicative ($\xi = 1$).
- SCC and carbon tax more upfront if EIS = ∞ and CRIIA = 0.
- Climate policy not much affected if:
  - the initial capital stock K_0 is half the size (100 not 200 trillion $).

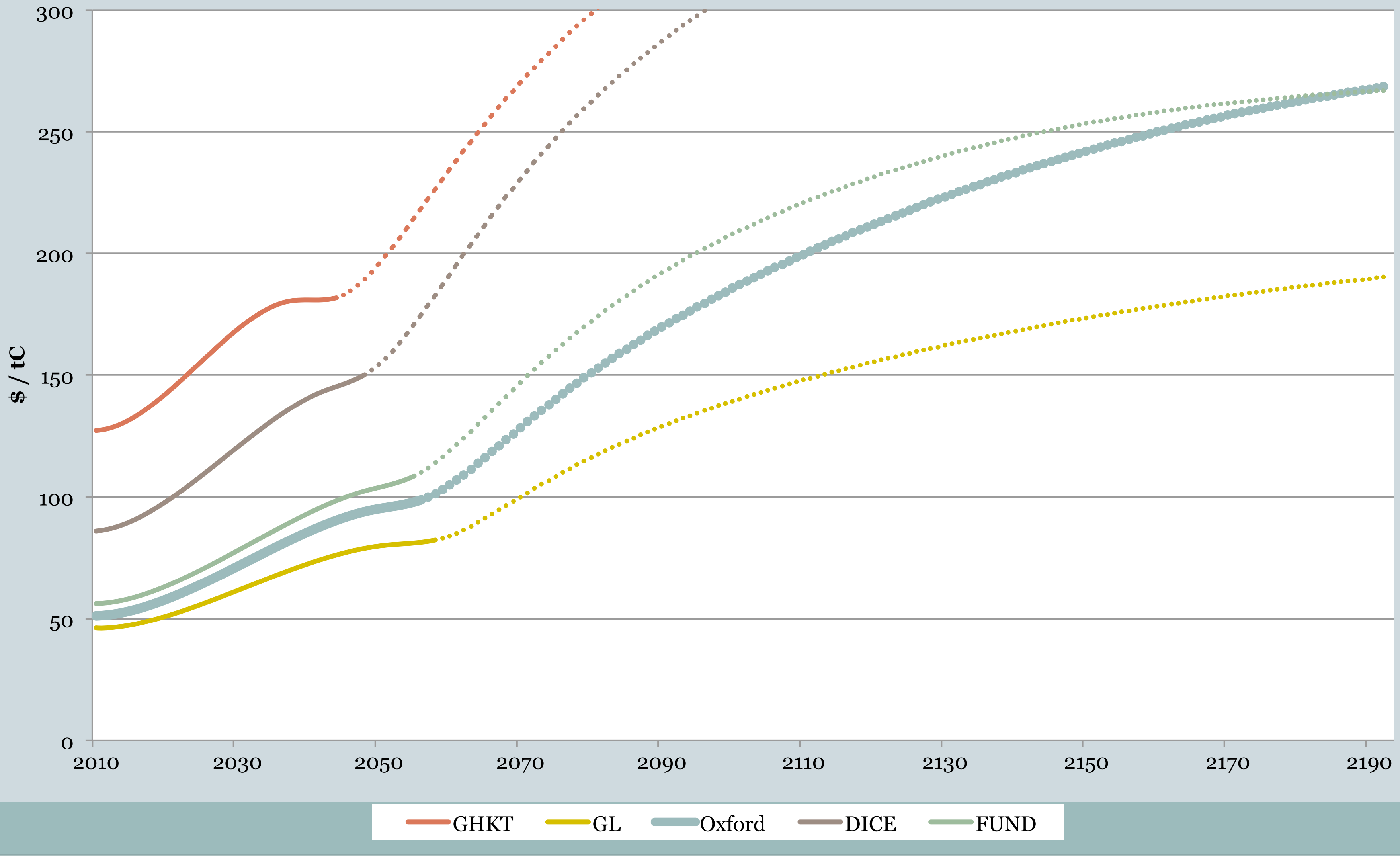
Robustness w.r.t. climate models (also based on joint work with Armon Rezai)

- Many different estimates of the SCC from many IAMs. Much of this is due to differences in the geo-physics and carbon cycles, which are often treated by economists as black boxes.
- Hence, we need robustness checks of optimal climate policies w.r.t. prominent climate cycles:
  - Oxford cycle (Allen et al., 2013)
  - FUND (Anthoff and Tol, 2009)
  - DICE (Nordhaus, 2014)
  - GL (Gerlagh and Liski, 2014)
  - GHKT (Golosov et al., 2014)

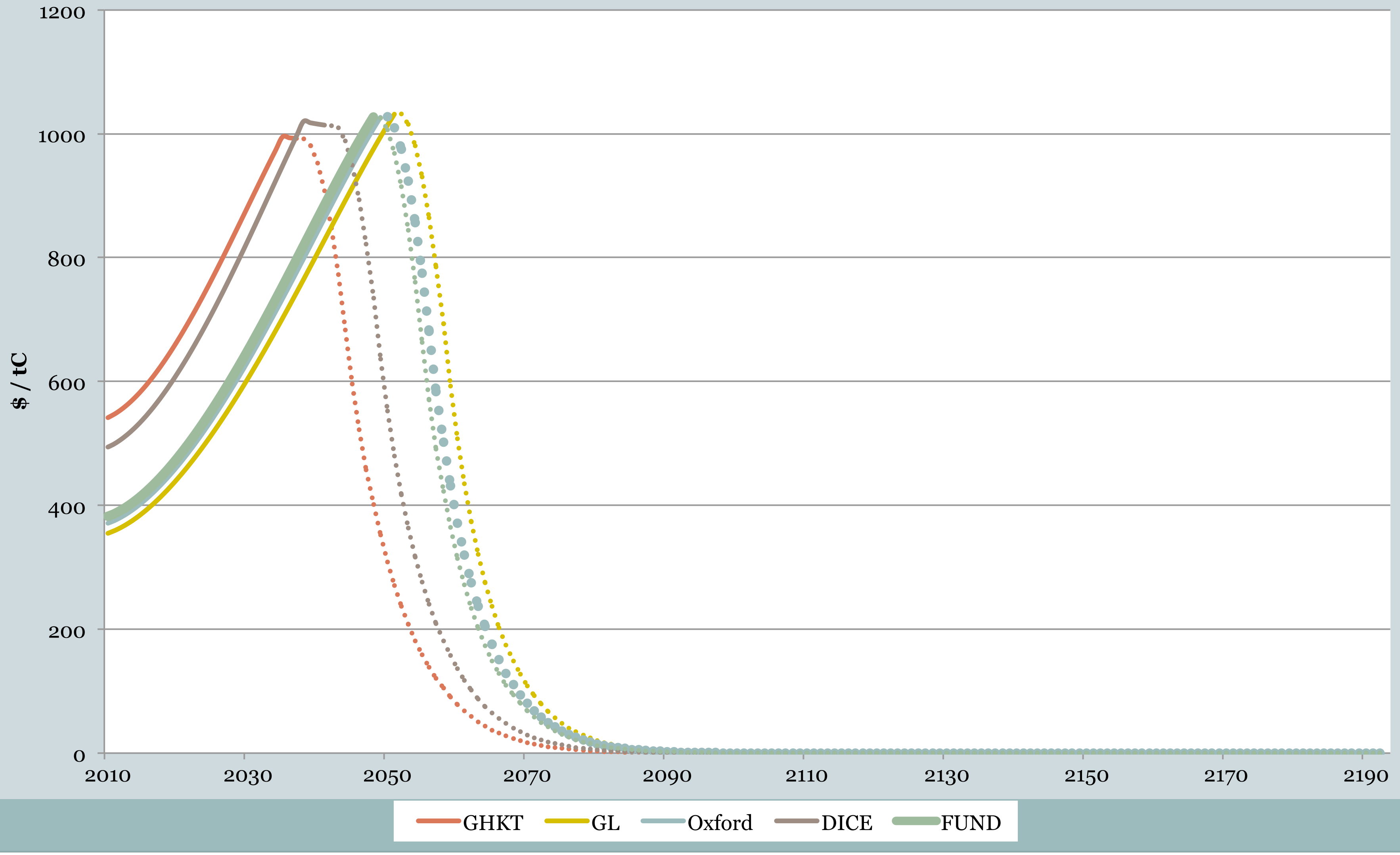
Robustness – Temperature



Little Robustness of the SCC to Carbon Cycle



Larger Robustness of Renewable Subsidy to Carbon Cycle



Sensitivity to carbon cycle

- Oxford model closest to geo-sciences. Best approximation of diffusive and advective forces governing carbon and temperature cycles between atmospheric and oceanic layers.
- Lowest Transient Climate Response (TCR), upward and downward.
- The climate cycle of FUND and GL exhibits higher TCR but also faster recovery.
- DICE appears very sensitive (highest TCR) and slow recovery.
- GHKT lacks temperature lag and recovers extremely fast.

- The optimal SCC mirrors these temperature responses.

SOME THEORY HELPS TO EXPLAIN

- Why weak Green Paradox effects are strong if fossil fuel demand responds strong and fossil fuel supply (reserves) responds weakly to prices.
- That then a future carbon tax accelerates heating in short run quite a bit and depresses welfare as not much carbon is locked up, especially if the ecological discount rate is high. Taxing assets owned by oil barons will then be an effective policy.
- But that if supply is very price elastic and the discount rate is small, a future carbon tax boosts welfare!
- Why Green Paradox effects are weakened in general equilibrium due to a fall in the global interest rate.

AND WHY

- The second-best optimal future carbon taxes is set *below* the Pigouvian tax if the current carbon is set too low as this mitigates Green Paradox effects.
- It pays to clobber the oil barons with an import tariff, especially if their reserves do not respond much to prices. Ministers of finance like carbon taxes even if they don’t care for climate.
- How carbon leakage and the Green Paradox interact.
- How presence of non-Kyoto countries affect setting of optimal unilateral carbon taxes.

Two-period, two-country model

- 2 periods: only assets are bonds (no physical capital).
- Perfect international capital markets.
- Exploration investment at start of period 1, so reserves and cumulative carbon emissions are endogenous.
- Industria (oil importers) and Oilrabia (oil exporters).
- Homothetic and identical preferences.
- Lump-sum taxes/subsidies residual mode of finance.
- Duality: easy comparative statics and welfare effects.
- See van der Ploeg (2016, JEEM). Cf. Eichner and Pethig (2011) and van der Meijden et al. (2015).

INDUSTRIA

- Unit-expenditure function of current and future final consumption goods: $e(\delta)$ with $\delta \equiv 1/(1+r)$.
- Present-value budget constraint:

$$e(\delta)U = C_1 + \delta C_2 = F(R_1) - q_1 R_1 + \delta\left[F(R_2) - q_2 R_2\right] + T \equiv \Pi$$

- Future and current consumption of final goods:

$$C_2 = e'(\delta)U = \theta(\delta)e(\delta)U/\delta, \quad C_1 = \left[1 - \theta(\delta)\right]e(\delta)U,$$

$$0 < \theta(\delta) \equiv \delta e'/e = \text{share of future goods in life-cycle basket} < 1$$

- Life-cycle welfare (PDV of utilities): U
- Oil demands: $F'(R_1) = q_1 \equiv p_1 + \tau_1, \quad F'(R_2) = q_2 \equiv p_2 + \tau_2.$

OILRABIA

- Choose exploration investment J and oil extraction rates R_1 and R_2 to maximize discounted profits
- $\Rightarrow$ Hotelling rule: $p_2 = (1+r^*)\, p_1$ or $p_1 = \delta^* p_2$
- Exploration: $p_2 S'(J) = 1 + r^*$ so $J = J(p_1),\ J'(p_1) > 0$

  and $S = S(p_1)$ with $S'(p_1) > 0.$

- Present-value budget constraint:

$$e(\delta^*)U^* = C_1^* + \frac{C_2^*}{1+r^*} = p_1 R_1 + \frac{p_2 R_2}{1+r^*} - J = p_1 S - J \equiv \Pi^*(p_1), \quad \Pi^{*\prime}(p_1) = S > 0$$

- Future and current consumption of final goods:

$$C_2^* = e'(\delta^*)U^* = \theta(\delta^*)e(\delta^*)U^* / \delta^*, \quad C_1^* = \left[1 - \theta(\delta^*)\right] e(\delta^*)U^*$$

Market equilibrium

- Capital market: $r^* = r$
- Oil market (OME):

$$R_1(p_1+\tau_1) + R_2\left((1+r)p_1+\tau_2\right) = S(p_1), \quad q_1 \equiv p_1+\tau_1$$

- Goods markets (GME):

$$\frac{C_2+C_2^*}{C_1+C_1^*} = \frac{\theta(r)}{1-\theta(r)}(1+r) \equiv \Theta(r) = \frac{F\left(S(p_1-\tau_1)-R_1(p_1+\tau_1)\right)}{F\left(R_1(p_1+\tau_1)\right)-J(p_1)}, \quad \Theta' > 0.$$

with $\Theta = \left[\beta(1+r)\right]^{\frac{1}{EIS}}$ and $\Theta'(r) = \delta\Theta / EIS > 0$ for power utility.

- Solve for p_1 & r (or δ) from OME & GME given τ_1 & τ_2

Comparative statics: OME locus

Define

$$\varepsilon_t^D \equiv -\frac{q_t R'(q_t)}{R_t} > 0, \quad \varepsilon^S \equiv \frac{p_1 S'(p_1)}{S} > 0 \text{ and } \Delta \equiv \tau_2 - (1+r)\tau_1,$$

so

$$dq_1 = \Upsilon^I d\tau_1 - \Upsilon^G (d\tau_2 + p_1 dr), \quad dp_1 = -(1-\Upsilon^I) d\tau_1 - \Upsilon^G (d\tau_2 + p_1 dr)$$

$$dS = \frac{S}{p_1}\varepsilon^S dp_1 \text{ and } dR_1 = -\frac{R_1}{q_1}\varepsilon_1^D dq_1,$$

where $0 < \Upsilon^I < 1$ and $0 < \Upsilon^G < 1$.

At zero taxes: $\Upsilon^I = \dfrac{\frac{R_2}{S}\varepsilon^D + \varepsilon^S}{\varepsilon^D + \varepsilon^S}, \quad \Upsilon^G = \dfrac{R_2}{S}\dfrac{\varepsilon^D}{\varepsilon^D + \varepsilon^S}.$

Interpretation: tax incidence

- A current carbon tax is shifted more to Oilrabia if the price elasticity of supply is small and that of demand is large. Less of the carbon taxes is then borne by consumers in Industria:

$$\text{low value of } \frac{dq_1}{d\tau_1} = \Upsilon^I \quad \text{and} \quad \text{high value of } -\frac{dp_1}{d\tau_1} = 1 - \Upsilon^I .$$

- Partial equilibrium Green Paradox effect is big if oil supply is more inelastic and demand more elastic:

$$-\frac{dq_1}{d\tau_2} = \Upsilon^G = \frac{\delta R_2 \varepsilon_2^D}{R_1 \varepsilon_1^D + R_2 \varepsilon_2^D + S \varepsilon^S} \quad \text{and} \quad \frac{dR_1}{d\tau_2} = \frac{q_1}{R_1} \varepsilon_1^D \Upsilon^G \ \text{large.}$$

Comparative statics: GME locus

$$\Upsilon^D dr = dp_1 + (1-\Upsilon^S)d\tau_1, \text{ where}$$

$$0 < \Upsilon^S \equiv \frac{\left(\Theta + \frac{q_2}{p_1}\right)S\varepsilon^S}{\left(\Theta + \frac{q_2}{p_1}\right)S\varepsilon^S + \left(\Theta + \frac{q_2}{q_1}\right)R_1\varepsilon_1^D} < 1 \text{ and } \Upsilon^D \equiv \frac{(C_1 + C_1^*)\Theta'(r)}{\left(\Theta + \frac{q_2}{p_1}\right)S\varepsilon^S + \left(\Theta + \frac{q_2}{q_1}\right)R_1\varepsilon_1^D} > 0.$$

With p_1, a higher current carbon tax boosts future net production and curbs current net production of final goods, so relative price of future final goods has to fall to clear goods markets. This requires a higher interest rate to shift demand for final goods from the present to the future.

General equilibrium effects

Solution follows from intersection of OME and GME loci:

$$dq_1 = \Gamma^I d\tau_1 - \Gamma^G d\tau_2 \quad \text{and} \quad dr = \Gamma^1 d\tau_1 - \Gamma^2 d\tau_2,$$

where

$$0 < \Gamma^I < \Upsilon^I < 1, \quad 0 < \Gamma^G \equiv \frac{\Upsilon^D}{\Upsilon^D + p_1\Upsilon^G}\Upsilon^G < \Upsilon^G,$$

$$\Gamma^1 \equiv \frac{\Upsilon^I - \Upsilon^S}{\Upsilon^D + p_1\Upsilon^G}(>)0, \quad \text{and} \quad \Gamma^2 \equiv \frac{\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} > 0.$$

At $\tau_1 = \tau_2 = 0$, $\Upsilon^I > \Upsilon^S$, $\Gamma^1 > 0$ and $\Gamma^I < \Upsilon^I$.

Partial equilibrium results ($\Gamma^1 = \Gamma^2 = 0$) emerge if $\Upsilon^D \to \infty$, i.e., if $\Theta'(r) \to \infty$ or $IES \to 0$ or $IIA \to \infty$.

Tax incidence and Green Paradox in general equilibrium

- Less of current carbon tax is borne by Industria's consumers, especially if demand is relatively more elastic than supply and much of oil extraction takes place today. The reason is that a current carbon tax *pushes up* the interest rate, which shifts oil depletion from the future to the present: $\Gamma^I < \Upsilon^I$
- The Green Paradox effect resulting from a future carbon tax is weakened in general equilibrium as the interest rate is *pushed down*: $\Gamma^G < \Upsilon^G$

Three effects of a future carbon tax:

- **Green Paradox effect**: boosts future consumer price of oil and cuts producer oil price, especially if incidence is mostly on Oilrabia (elasticity of supply low and of demand high) $\Rightarrow$ brings forward oil production and carbon emissions. Bad for welfare.
- **Intertemporal terms of trade effect**: relative fall in future supply of goods pushes up future price of final goods. The cut in r induces Oilrabia to produce less today and more tomorrow. This weakens the Green Paradox effect.
- **Putting out of business effect**: higher carbon tax cuts producer price of oil and curbs exploitation investment, reserves and cumulative emissions, especially if the supply elasticity of oil reserves is high. Good for welfare, especially if the discount rate is low and supply elastic.

Welfare effects of a future carbon tax

- Green welfare loss $\equiv \quad \chi(R_1 + \beta S), \quad \chi > 0.$
- Change private global welfare (at zero taxes): $d(U + U^*) = 0.$
- Future carbon tax boosts welfare if $R_1\varepsilon^D < \beta S\varepsilon^S.$
- If $R_1\varepsilon^D > \beta S\varepsilon^S$ it curbs green and global welfare (strong Green Paradox).
- Note: if $\varepsilon^S = 0,$ always a strong Green Paradox.

Sinn's proposal for asset tax

- Industria can tax asset holdings by Oilrabia at rate υ as to mitigate the Green Paradox ($r^* = r - \upsilon$ with increase in υ similar effect as cut in τ_2).
- This slows down oil extraction and decelerates global warming, but traps less fossil fuel in the earth and boosts cumulative carbon emissions.
- Hence, if $R_1\varepsilon^D > \beta S\varepsilon^S$, a future carbon tax hurts green and global welfare but an asset tax boosts green and global welfare. And vice versa.

Balanced carbon tax hike ($\Delta = 0$)

- A carbon tax that rises over time at the rate of interest does not affect demand for oil, so is neutral if supply is inelastic ($\varepsilon^S = 0$).
- If oil supply is elastic ($\varepsilon^S > 0$), more oil is 'stranded'. This pushes up current consumer oil price and cuts *current* oil demand and emissions. The cut in producer price of oil depresses oil exploration and *cumulative* carbon emissions. Both effects boost welfare.
- Interest rate falls if reserves fall relatively a lot.

A growing carbon tax

- A carbon tax that grows *faster* than the rate of interest ($\Delta > 0$) induces weak Green Paradox effects and cuts welfare if reserves are inelastic:

$$dq_1 = \left[\Gamma^I - (1+r)\Gamma^G\right] d\tau_1 - \Gamma^G d\Delta \rightarrow -\Gamma^G d\Delta < 0, \quad dR_1 > 0,$$

$$d(U + U^* - \chi R_1) = -\chi dR_1 = -\chi \varepsilon_1^D (R_1 / q_1) \Gamma^G d\Delta < 0.$$

- A carbon tax that grows *slower* than the rate of interest ($\Delta < 0$) curbs current emissions and boosts welfare even if reserves are inelastic.

Marginal change in global welfare

- Change in global private welfare:

$$U + U^* = \frac{F(R_1) + \delta F(R_2) - J(q_1 - \tau_1)}{e(\delta)} \quad \Rightarrow$$

$$d(U + U^*) = \left[\tau_1 dR_1 + \delta\tau_2 dR_2\right] / \, e(\delta).$$

- Hence, change in global total welfare is:

$$d(U + U^*) - \chi(dR_1 + \beta dS) = \left(\frac{\tau_1 - \delta\tau_2}{e} - \chi\right) dR_1 + \left(\frac{\delta\tau_2}{e} - \chi\beta\right) dS.$$

- At zero carbon taxes this becomes $-\chi(dR_1 + \beta dS)$.

Global first-best carbon taxes

- Total change in global welfare is zero if:

$$\tau_1^F = \tau_1^P = (1+\beta)\chi e \text{ and } \tau_2^F = \tau_2^P = \frac{\chi\beta}{\delta}e.$$

- Pigouvian carbon taxes are PDV of all future marginal climate damages: high if the social discount rate is small.
- Present carbon tax rises with *e* and thus falls with the interest rate. Future carbon tax also rises directly with interest rate. If *EIS* = 1, this effect dominates.
- If oil reserves are fixed, *dS* = 0, first best with either a carbon tax today or future carbon subsidy: $\tau_1 - \delta\tau_2 = \chi e$
- No Green Paradox effects.

Globally second-best optimal future carbon tax

- How does setting the current carbon tax too low affect the second-best optimal future carbon tax:

$$\tau_2^S = \tau_2^P - \frac{R_1\varepsilon_1^D}{\dfrac{p_1 S}{p_2}\varepsilon^S + R_1\varepsilon_1^D}\left(\frac{\tau_1^P - \bar{\tau}_1}{\delta}\right) < \tau_2^P .$$

- Postponed second-best carbon tax does not over-compensate. It falls short of the future Pigouvian tax, especially if price elasticity of oil demand is large and that of oil supply is small.
- Requires commitment to future carbon tax!

Change in Industria’s welfare

$$-\frac{R_1}{q_1 e}\left[\boldsymbol{\tau}_1 - \boldsymbol{\tau}_1^P - \delta(\boldsymbol{\tau}_2 - \boldsymbol{\tau}_2^P)\right]\varepsilon_1^D dq_1 + \frac{S}{p_2 e}(\boldsymbol{\tau}_2 - \boldsymbol{\tau}_2^P)\varepsilon^S(dq_1 - d\boldsymbol{\tau}_1) - dU^*$$

$$\text{with } dU^* = \frac{S}{e}(dq_1 - d\boldsymbol{\tau}_1) + \delta\theta U^* dr.$$

To get second-best unilateral carbon taxes, substitute comparative statics in for dq_1 and dr, and then set coefficients in front of $d\tau_1$ and $d\tau_2$ to zero.

Future carbon tax above first best always boosts welfare, but not so for current carbon tax

- **Putting oil exporters out of business:** Fall in oil exploration (lower J and S) due to fall in producer price of oil (p_1) either via usual tax shifting for the current carbon tax or via Green Paradox for future carbon tax. This cuts Oilrabia's welfare (U^*) and boosts private welfare of Industria (U).
- **Change in the intertemporal terms of trade:** XDG1 and thus a higher price of current goods (higher r and lower e) and boost of Oilrabia' welfare for a current carbon tax *and* XDG2 and thus a higher price of future goods (lower r and higher e) and fall in Oilrabia' welfare for a future carbon tax.
- Two effects operate in same direction for *future* carbon tax, so Industria' welfare unambiguously rises.
- But for a *current* carbon tax, the increase in Industria' welfare from 'putting Oilrabia out of business' is dampened by negative 'intertemporal terms of trade' effect on welfare.

Unilateral optimal carbon taxes

$$\tau_2^U = \underbrace{\tau_2^P}_{\text{Pigouvian part}} + \underbrace{\frac{p_2}{\varepsilon^S}}_{\text{pure import part}} + \underbrace{\frac{p_2}{\varepsilon^S}\frac{\theta\delta e C^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}}_{\text{intertemporal terms of trade correction future carbon tax}} > \underbrace{\tau_2^P + \frac{p_2}{\varepsilon^S}}_{\text{partial equilibrium carbon tax}} > \tau_2^P$$

Note: $\varepsilon^S = 0 \Rightarrow \Upsilon^S = 0,\ EIS \rightarrow \infty \Rightarrow \Gamma^2 \rightarrow 0.$

$$\tau_1 = \underbrace{\tau_1^P}_{\text{Pigouvian part}} + \underbrace{\frac{p_1}{\varepsilon^S}}_{\text{pure import tariff}} + \underbrace{\frac{p_1}{\varepsilon^S}\frac{\theta\delta e C^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}}_{\text{present value of ITT correction future carbon tax (Hotelling)}} - \underbrace{\frac{q_1}{\varepsilon_1^D}\frac{\theta\delta e C^*}{R_1}\frac{\Gamma^2(1-\Upsilon^S)}{\Gamma^G}}_{\text{ITT correction current carbon tax}}.$$

Are unilateral carbon taxes excessive?

- Industria wants to capture some of Oilrabia's rent: adds *import tariff* on oil which puts oil exporters further out of business. If Oilrabia cannot easily adjust reserves downwards (low ε^S), this tariff is high. Minister of Finance love this.
- ITT effect pushes up *future* tariff, but pushes down *current* tariff tax is pushed *down*. These opposing effects are stronger if oil demand has a lower price elasticity and *IIA* is high. They tilt tariff components from present to future.
- Without commitment: incentive to renege and push up tariff in future to clobber Oilrabia even more.
- Paths of oil use and carbon emissions are below those of first best. More oil reserves are left abandoned than in first best: import tariff's are the greens' best friend.

CARBON LEAKAGE FROM OME AND GME

$$R_1^K(p_1+\tau_1)+R_1^N(p_1)+R_2^K\left((1+r)p_1+\tau_2\right)+R_2^N\left((1+r)p_1\right)=S(p_1),$$

$$(C_2^K+C_2^N+C_2^*)/(C_1^K+C_1^N+C_1^*)=\Theta(r)=$$

$$\frac{F_2^K\left(S(p_1)-R_1^K(p_1+\tau_1)-R_1^N(p_1)-R_2^N\left((1+r)p_1\right)\right)+F_2^N\left(R_2^N\left((1+r)p_1\right)\right)}{F_1^K\left(R_1^K(p_1+\tau_1)\right)+F_1^N\left(R_1^N(p_1)\right)-J(p_1)},$$

- Fall in emissions in *K* is partially offset by higher current and future emissions in *N*. Green welfare increases iff $R_1^K\varepsilon_1^{KD}+R_1^N\varepsilon_1^{ND}<\beta S\varepsilon^S$.
- Unilateral welfare can rise despite strong GP:

$$\frac{d(U^K-\Omega)}{d\tau_2}=\left[\frac{\chi}{p_1}\left(\beta S\varepsilon^S-R_1^K\varepsilon_1^{KD}-R_1^N\varepsilon_1^{ND}\right)+\frac{R_1^K+R_2^K}{e}+\frac{\delta^2}{e\Upsilon^D}\left\{F_2^K(R_2^K)-C_2^K\right\}\right]\Gamma^G.$$

Globally altruistic second-best carbon tax

- Both rent grabbing effect and ITT effect (proportional to future trade balance of *K* countries) of a future carbon tax.
- Globally altruistic carbon taxes are too low as *N* sets carbon taxes too low, especially if oil producers bear most of burden, Green Paradox strong and *N* large:

$$\tau_1^{K,GA} = \tau_1^P - (1-\Upsilon^I)\left(\frac{(\tau_1^P - \bar{\tau}_1^N)R_1^N \varepsilon_1^{ND} / q_1^N + (\tau_2^P - \bar{\tau}_2^N)R_2^N \varepsilon_2^{ND} / q_2^N}{R_1^K \varepsilon_1^{KD} / q_1^K}\right)\Lambda < \tau_1^{FB} = \tau_1^P,$$

$$\tau_2^{K,GA} = \tau_2^P - \Upsilon^G\left(\frac{(\tau_1^P - \bar{\tau}_1^N)R_1^N \varepsilon_1^{ND} / q_1^N + (\tau_2^P - \bar{\tau}_2^N)R_2^N \varepsilon_2^{ND} / q_2^N}{\delta R_2^K \varepsilon_2^{KD} / q_2^K}\right)\Lambda < \tau_2^{FB} = \tau_2^P.$$

Unilaterally second-best optimal carbon tax

- If *K* maximizes its own welfare instead of global welfare, we get the unilaterally optimal taxes. These exceed the globally altruistic taxes:

$$\boldsymbol{\tau}_1^{K,U} = \boldsymbol{\tau}_1^{P} + (1-\Upsilon^{I})\left[\frac{q_1^K(R_1^K+R_2^K)-(\boldsymbol{\tau}_1^P-\bar{\boldsymbol{\tau}}_1^N)R_1^N\varepsilon_1^{ND}/q_1^N-(\boldsymbol{\tau}_2^P-\bar{\boldsymbol{\tau}}_2^N)R_2^N\varepsilon_2^{ND}/q_2^N}{R_1^K\varepsilon_1^{KD}/q_1^K}\right]\Lambda,$$

$$\boldsymbol{\tau}_2^{K,U} = \boldsymbol{\tau}_2^{P} + \Upsilon^{G}\left[\frac{q_2^K(R_1^K+R_2^K)-(\boldsymbol{\tau}_1^P-\bar{\boldsymbol{\tau}}_1^N)R_1^N\varepsilon_1^{ND}/q_1^N-(\boldsymbol{\tau}_2^P-\bar{\boldsymbol{\tau}}_2^N)R_2^N\varepsilon_2^{ND}/q_2^N}{\delta R_2^K\varepsilon_2^{KD}/q_2^K}\right]\Lambda.$$

- They exceed the Pigouvian rates if rent grabbing effects dominate carbon free-riding effects.

CONCLUSIONS

- Future carbon tax accelerates global warming and is weakened by lower interest rate, but locks up more carbon and curbs peak global warming. Green welfare improves if price elasticity of supply of oil reserves is relatively large and discount rate relatively small.
- Sinn’s asset holding tax reverses Green Paradox if reserves are inelastic.
- Second-best future carbon tax is set below Pigouvian tax if current carbon taxes are set too low.
- Optimal unilateral carbon taxes capture part of oil rents and put oil barons out of business, especially if exploration investments are not very sensitive to oil prices.
- Unilateral carbon taxes are harmful and can lower global welfare. They are time inconsistent once exploration investment is sunk, since there is an incentive to renege and push them up even more in the future.
- If some countries price carbon too low, others price too low also especially if oil producers carry most of burden and Green Paradox effects are strong

Strategic issues

- Oil importers want to cream off the rents of oil exporters, but oil exporters can cream off climate rents of oil importers if they can set oil prices in a monopolistic manner. This makes carbon taxes less excessive than the unilateral optimal carbon taxes.
- A Nash equilibrium in the carbon tax and oil price can then be calculated and contrasted with a cooperative equilibrium (Tahvonen, 1995; Wirl, 1995; Rubio and Escriche, 2001; Liski and Tahvonen, 2004; Kagan, van der Ploeg and Withagen, 2015).
- Also games with limit pricing in investment in renewables (Hoel; Jaakkola, 2016).

Future: more work on second best

- Participating and non-participating countries in international climate deals when international transfers are not complete.
- National adaptation if global carbon pricing insufficient.
- Distorting taxes especially if public sector is large.
- Overlapping generations without operational bequest motive.
- Political economy of climate policies.
- Procrastination of climate policies
- Calibration and empirical assessment of gains from commitment.

- Requires numerical solutions of intricate dynamic programming problems.

CLIMATE TIPPING AND ECONOMIC GROWTH

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How to model catastrophes?

- Chance that a discontinuous change in damages or carbon cycle takes place. This can be abrupt as with shifts in monsoonal systems. But loss of ice sheets resulting in higher sea levels have slow onsets and can take millennium or more to have its full effect (Greenland 7m and Western Antarctica 3m, say) and may already be occurring.
- 9 big catastrophes are imminent, not all at same time (Lenton and Ciscar, CC, Nature).
- Collapse of the Atlantic thermohaline circulation is fairly imminent and might occur at relatively low levels of global warming. This affects regions differently, but we capture this with a negative TFP shock.
- We look at TFP calamity and also at K, P and climate sensitivity calamities. Expected time of calamity falls with global warming.

Probabilities of Various Tipping Points from Expert Elicitation

Possible Tipping Points	Duration before effect is fully realized (in years)	Additional Warming by 2100		
		0.5-1.5 C	1.5-3.0 C	3-5 C
Reorganization of Atlantic Meridional Overturning Circulation	about 100	0-18%	6-39%	18-67%
Greenland Ice Sheet collapse	at least 300	8-39%	33-73%	67-96%
West Antarctic Ice Sheet collapse	at least 300	5-41%	10-63%	33-88%
Dieback of Amazon rainforest	about 50	2-46%	14-84%	41-94%
Strengthening of El Niño-Southern Oscillation	about 100	1-13%	6-32%	19-49%
Dieback of boreal forests	about 50	13-43%	20-81%	34-91%
Shift in Indian Summer Monsoon	about 1	Not formally assessed		
Release of methane from melting permafrost	Less than 100	Not formally assessed.		

Messages and aims

- Chance of catastrophe can lead to much higher *SCC* without a very low discount rate provided hazard rises sharply with temperature $\Rightarrow$ to avert risk.
- There is also a social benefit of capital (*SBC*) which gives a rationale for precautionary capital accumulation $\Rightarrow$ to be better prepared.
- Calibrate a global IAM with Ramsey growth with both catastrophic and marginal climate damages.
- Show role of convexity of the hazard function.
- Show effect of more intergenerational inequality aversion and thus more risk aversion on *SCC* and *SBC*: i.e., on carbon tax and capital subsidy.

Backward induction: before disaster

- For time being, damages only result from calamities.
- Solve post-catastrophe problem as standard Ramsey problem to give post-calamity value function: $V^A(K,\pi)$.
- Solve before-catastrophe problem from the HJB:

$$\rho V^B(K,P) = \underset{C,E,R}{\mathrm{Max}} \{ U(C) + H(P)[V^A(K,\pi) - V^B(K,P)] +$$

$$V_K^B(K,P)[AF(K,E,R) - dE - cR - C - \delta K] + V_P^B(K,P)(\psi E - \gamma P)\}$$

with optimality conditions

$$U'(C^B) = V_K^B(K,P), \quad AF_E(K,E,R) = d + \tau, \quad \tau \equiv -\psi V_P^B(K,P) / V_K^B(K,P) > 0,$$

$$AF_R(K,E,R) = c, \quad AF_K(K,E,R) - \delta \equiv r.$$

Precautionary saving and curbing risk of calamity

- The Euler equation has a precautionary return θ or social benefit of capital (*SBC*):

$$\dot{C} = \sigma(r + \theta - \rho)C \quad \text{with} \quad r = Y_K^B(K, d + \tau, c, A)$$

$$\theta = H(P)\left[\frac{V_K^A(K,\pi)}{U'(C)} - 1\right] = H(P)\left[\left(\frac{C^B}{C^A}\right)^{1/\sigma} - 1\right] > 0.$$

- The *SCC* is:

$$\tau(t) = \int_t^\infty \psi H'\big(P(s)\big)\frac{V^B(s) - V^A(s)}{U'\big(C^B(s)\big)}\exp\left(-\int_t^s \big[r(s') + \theta(s') + \gamma + H\big(P(s')\big)\big]ds'\right)ds$$

$$= \left\{\int_t^\infty \psi H'\big(P(s)\big)\big[V^B(s) - V^A(s)\big]\exp\left(-\int_t^s \big[\rho + \gamma + H\big(P(s')\big)\big]ds'\right)ds\right\} / U'\big(C^B(t)\big).$$

Interpretation

- ‘Doomsday’ scenario has $V^A = 0$, so the discount rate is *increased* $\Rightarrow$ frantic consumption and less investment. Mr. Bean!
- But if world goes on after disaster, precaution is needed. Since consumption will fall after disaster, *SBC* > 0 and the discount rate is *reduced*. This calls for precautionary capital accumulation (if necessary internalized via a capital subsidy)
- The *SBC* is bigger if the hazard and size of the disaster are bigger.
- And if intergenerational inequality aversion (*CRIIA)* or relative prudence (1+*CRIIA*) is bigger.

Alternative expressions: discounting goods units instead of utils

$$\tau(t) = \underbrace{-\psi\int_t^\infty A'\big(P(s)\big)F(s)e^{-\int_t^s\left[r+\theta+\gamma+H(P(s')\right]ds}ds}_{\text{conventional Pigouvian social cost of carbon}}$$

$$\underbrace{-\psi\int_t^\infty \frac{H\big(P(s)\big)V_P^A\big(K(s)-\Omega,\Delta,P(s)+\Xi\big)e^{-\int_t^s\left[r+\theta+\gamma+H(P(s')\right]ds}}{U'\big(C(s)\big)}ds}_{\text{'raising the stakes' effect}}$$

$$\underbrace{+\psi\int_t^\infty \frac{H'\big(P(s)\big)\left\{V^B(s)-V^A(s)\right\}e^{-\int_t^s\left[r+\theta+\gamma+H(P(s')\right]ds}}{U'\big(C(s)\big)}ds}_{\text{'risk averting' effect}}, \quad 0 \le t < T.$$

Golosov et al. (2014, *Ectra*): first term with $\sigma = 1, \theta = H(P) = 0 \Rightarrow = \dfrac{0.00238\psi GDP}{\rho+\gamma}$

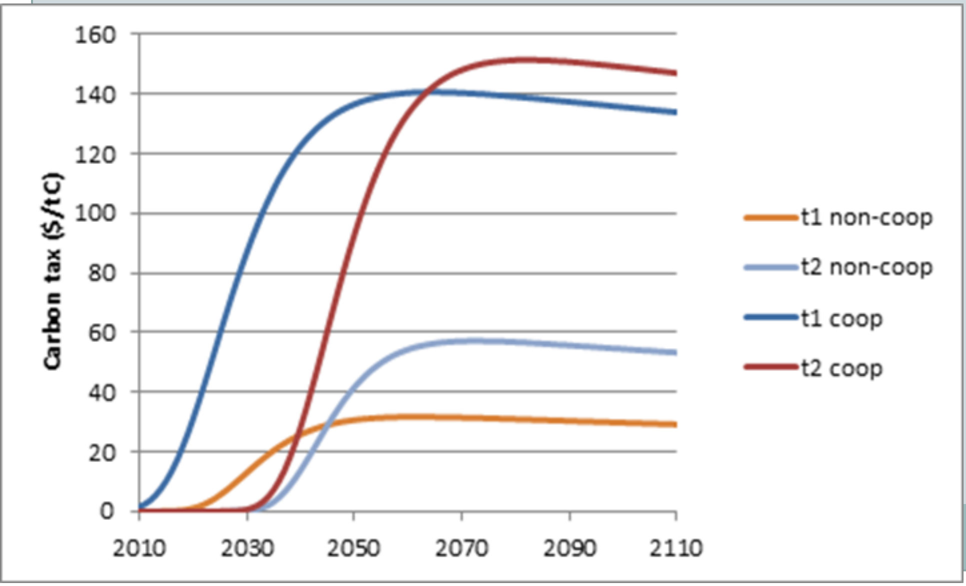
(they also need $A(P) = e^{-0.00238P}$, 100% depreciation & Cobb-Douglas production)

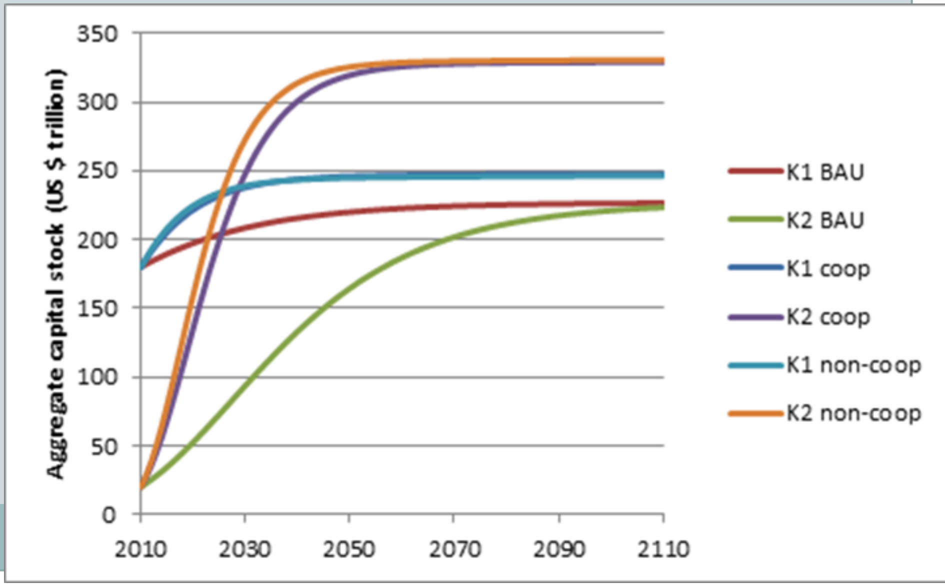
Insights

- Small risks of climate disasters may lead to a much bigger *SCC* even with usual discount rates. Rationale is to avoid risk.
- Also need for precautionary capital accumulation.
- Need estimates of current risks of catastrophe and how these increase with temperature.
- Recoverable shocks such as *P* or *K* calamities are less problematic.
- Catastrophic changes in system dynamics unleashing positive feedback may be much more dangerous than *TFP* calamities.

Extension: North-South perspective

- Carbon taxes rise in line with GDP; lots of precaution.
- South is poor and is hit more by global warming than North ⇒ taxes carbon later and eventually more.
- Big non-cooperative bias in carbon tax, but not in precautionary return on capital.





Other extensions

- Adaptation capital (sea walls, storm surge barriers) increases with global warming: trade-off with productive capital.
- Positive feedback in the carbon cycle changes carbon cycle dynamocs (e.g., Greenland or West Antarctica ice sheet collapse).
- Multiple tipping points with different hazard functions and impact lags (Cai, Judd, Lontzek; Lemoine and Traeger; NCC, 2016). ‘Strange’ cost-benefit analysis (Pindyck, AER).
- Learning about probabilities of tipping points, but also about whether they exist all (cf. ‘email-problem’). How to respond to a tipping point which may never materialize?
- Exhaustibility of fossil fuel: so anticipation of tip ⇒ Green Paradox.
- Second-best issues: Green Paradox can lead to ‘runaway’ global warming if system is tipped due to more rapid depletion of oil, gas and coal in face of a future tightening of climate policy (Winter, 2014, JEEM).