TRANSITIONAL RISKS
Drivers of climate policy, carbon budgets and energy transitions

THE ENERGY TRANSITION, NDCS, AND THE POST COP-21
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Motivation

- Climate policy is important for everyone.
- However, most IAMs are difficult to comprehend and it is difficult to see exactly on what key assumptions outcomes are driven by. So results difficult to communicate.
- This and the lack of a proper scientific basis is why many IAMs have been criticized: Pindyck, Stern and Weitzman.
- We want to clearly show what the ethical, economic, technological and geo-physical drivers are of the price of carbon, mitigation, abatement and peak global warming as well as the optimal timing of energy transitions.
- This gives insight into carbon budgets and stranded assets.

Contributions

- Provide a transparent framework to generate simple, easy-to-understand and robust rules for the optimal price of carbon, mitigation, abatement, cumulative emissions and peak warming.
- Calibrate it to DICE/RICE of Nordhaus and generate numbers for optimal climate policy both with and without an international climate deal in place.
- Allow for generalised hyperbolic discounting and procrastination, so intertemporal tradeoffs in far future are evaluated with smaller discount rate than those in the present. This builds a bridge between high choice for discount rate used by Nordhaus and low one used by the Stern Review.
- As policy makers cannot commit themselves to those of other countries and cannot commit to their future selves, climate policy is much more lacklustre than it should.

Assumptions: technology

- Since Ramsey dynamics converges much faster than that of the carbon cycle, suppose output Y_t grows at trend rate $g > 0$ when calculating climate policy.
- Energy needed is $F_t = \gamma_0 \exp(-r_\gamma t)\, Y_t$.
- $(1-m_t)(1-a_t)F_t$ are emissions entering atmosphere, where m_t is mitigation rate (share of renewables) and a_t abatement rate (share of fossil fuel that's clean).
- Cost of mitigating and abating fossil fuel are:

$$mH_0 + \theta_m^{-1} m^{\theta_m} e^{-r_R t} H_1 \text{ and } \theta_a^{-1} A_1 e^{-r_A t} a_t^{\theta_a} \text{ with } \varepsilon_i = 1/(\theta_i - 1) > 0.$$

Assumptions: carbon cycle and damages

- Two-box cycle: a share β_0 = 0.2 of emissions stays up permanently in the atmosphere and the remainder is transient and decays at the rate of β_1 = 0.0023 GtC/year.
- The average lag before global mean temperature increases after an increase in total stock of atmospheric carbon is *Tlag* = 10 years.
- The flow damage of aggregate global warming for each TtC in the atmosphere is *d* \$ per T\$ of aggregate output, i.e., *d* = 0.019 \$/tC.

The globally optimal price of carbon

- Price of carbon grows at same rate as world GDP.
- It is high if growth-corrected social discount rate *SDR* is low: if society is relatively patient (low *RTI*), if future generations are richer than current ones ($g > 0$ if $IIA > 1$), and if *IIA* high. High growth in GDP implies high growth in damages and thus a lower SDR and higher price of carbon.
- Temperature lag depresses optimal price of carbon.

$$P_t = \tau Y_0 e^{gt} \text{ with } \tau = \left(\frac{\beta_0}{SDR} + \frac{1-\beta_0}{SDR+\beta_1} \right) \left(\frac{1}{1+SDR \times Tlag} \right) d$$

and $SDR = RTI + (IIA - 1)g$,

Optimal mitigation rate

- Optimal mitigation (share of renewable energy in total energy use) rises in price of carbon P_t and cost of unabated fossil fuel and falls with cost of renewable energies. Rises over time with growth of the economy g and specific technical progress in renewable energy production r_R but falls over time with technical progress in fossil fuel extraction r_F (e.g., horizontal drilling in shale gas production) and with technical progress in abatement r_A.

$$m_t = \left(\frac{G_0 e^{-r_F t} + \frac{1}{\theta_a} A_1 e^{-r_A t} a_t^{\theta_a} + (1 - a_t) P_t - H_0}{H_1 e^{-r_R t}} \right)^{\varepsilon_m}, \quad 0 \le m_t \le 1.$$

Optimal abatement (e.g., CCS)

- Optimal abatement (fraction of fossil fuel that is fully abated) increases in the price of carbon and reduces in the cost of abatement. Over time abatement thus increases with growth of the economy and with specific technical progress in abatement.

$$a_t = \left(P_t e^{r_A t} / A_1 \right)^{\varepsilon_a}, \ 0 \le a_t \le 1.$$

Hyperbolic discounting

- 74% choose fruit and 26% chocolate if they have it next week, but 30% and 70% if they have it now.
- People join gym for $75/month, but go only 4 times so effective cost is $19/visit. Whereas without joining they would only pay $10/visit on PAYG basis.
- Self wants to be patient and delay gratification, but actions indicate instant gratification.
- Hyperbolic discounting also explains dithering and procrastination in setting climate policy. So pricing carbon is put off.
- Can use this to bridge high present & low future discount rates.

Hyperbolic discounting: technically

- Hyperbolic discounting has $D(t) = (1 + at)^{-\frac{\rho}{a}}$.
- Exponential discounting (as $a \to 0$) has $D(t) = e^{-\rho t}$.
- Instantaneous discount rate is $\delta_t \equiv -D'(t) / D(t) = \rho / (1 + at)$.
- Calibrate short-run discount rate, ρ, to Nordhaus rate of 1.5% per year and long-run discount rate at t = 100 years to Stern rate of 0.1% per year, hence we calibrate a = 0.14%/year.
- Time inconsistency, so distinguish outcomes with and without commitment.

Calibration based on DICE/RICE

Ethical:
Rate of time impatience: RTI **= 1.5% per year**
Intergenerational inequality aversion and risk aversion: $IIA = RRA = 1.45$
Growth-corrected social discount rate: SDR **= 2.4% per year**
Hyperbolic discounting: ρ **= 1.5% per year,** a **= 0.14% per year**

Economic:
World economy: GDP_0 **= 73 T$,** g **= 2% per year**
Energy use per unit of world GDP: $\gamma = 1.4E^{-04}$ **tC/$,** r_γ **= 0 % per year**
Fossil fuel cost: G_o **= 515 $/tC,** r_E **= -0.1% per year**
Renewable energy cost: H_0 **= 515 $/tC,** H_1 **= 1150 $/tC,** $\theta_m = 2.8$, $\varepsilon_m = 0.55$, r_R **= 1.25% per year**
Abatement (CCS) cost: A_1 **= 2936 $/tC,** $\theta_a = 2$ **so** $\varepsilon_a = 1$, $r_A = r_R$ **= 1.25% per year**
Flow damage as fraction of world GDP: d **= 0.019 $/tC**

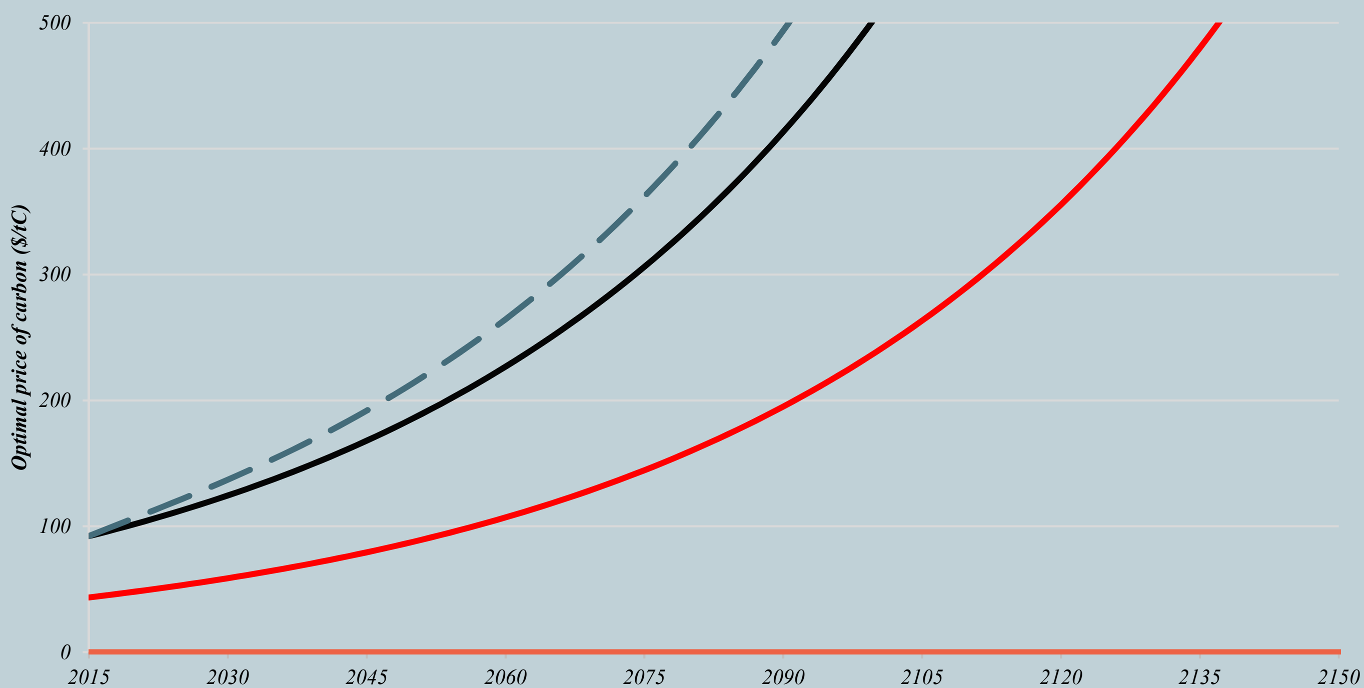
Geo-physical:
Coefficients permanent & transient box of carbon cycle: $\beta_0 = 0.2$, $\beta_1 = 0.0023$
Average lag between temperature/damages and carbon stock: $Tlag$ **= 10 years**
Transient climate response to cumulative emissions: $TCRE$ **= 2ºC/TtC**

Regional:
$d_{Africa} = 2.61\ d$, $d_{Europe} = 1.89$ d, $d_{US} = 0.3\ d$, $d_{China} = 0.15\ d$, $d_{ROW} = 1.13$ d
$GDP_{o,Africa}$ **= 2 T$,** $GDP_{o,Europe}$ **= 16.8 T$,** $GDP_{o,US}$ **= 18 T$,** $GDP_{o,China}$ **= 10.8 T$,**
$GDP_{o,ROW}$ **= 25.7T$**

Globally optimal price of carbon

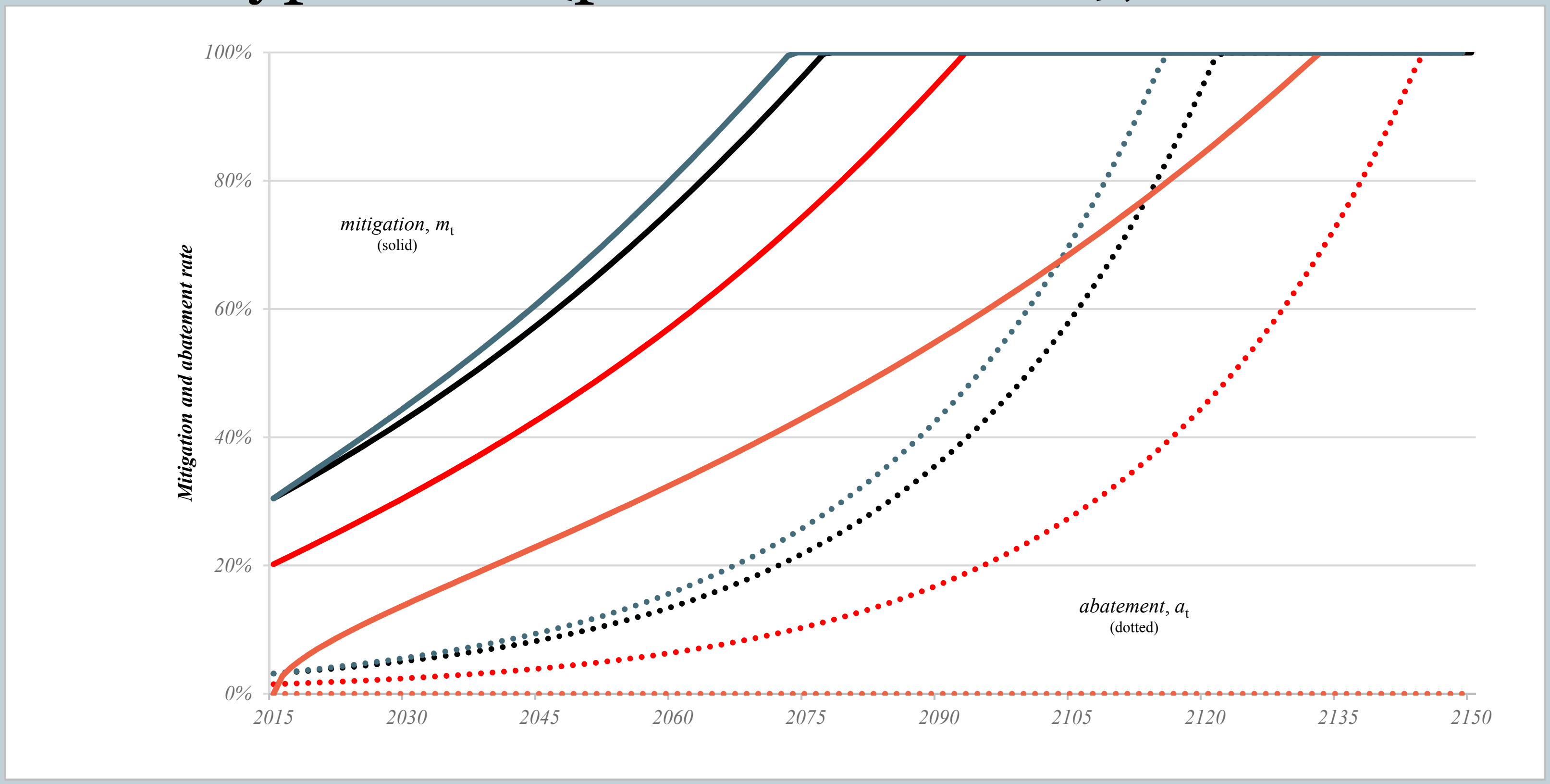
- Red = exponential discounting
- Black = hyperbolic discounting

(solid – no commitment, dashed – pre-commitment)



Mitigation (solid) and Abatement (dotted)

- Red = Exponential; Black = Hyperbolic (no commitm.)
- Blue = Hyperbolic (pre-commitment); Brown = BAU



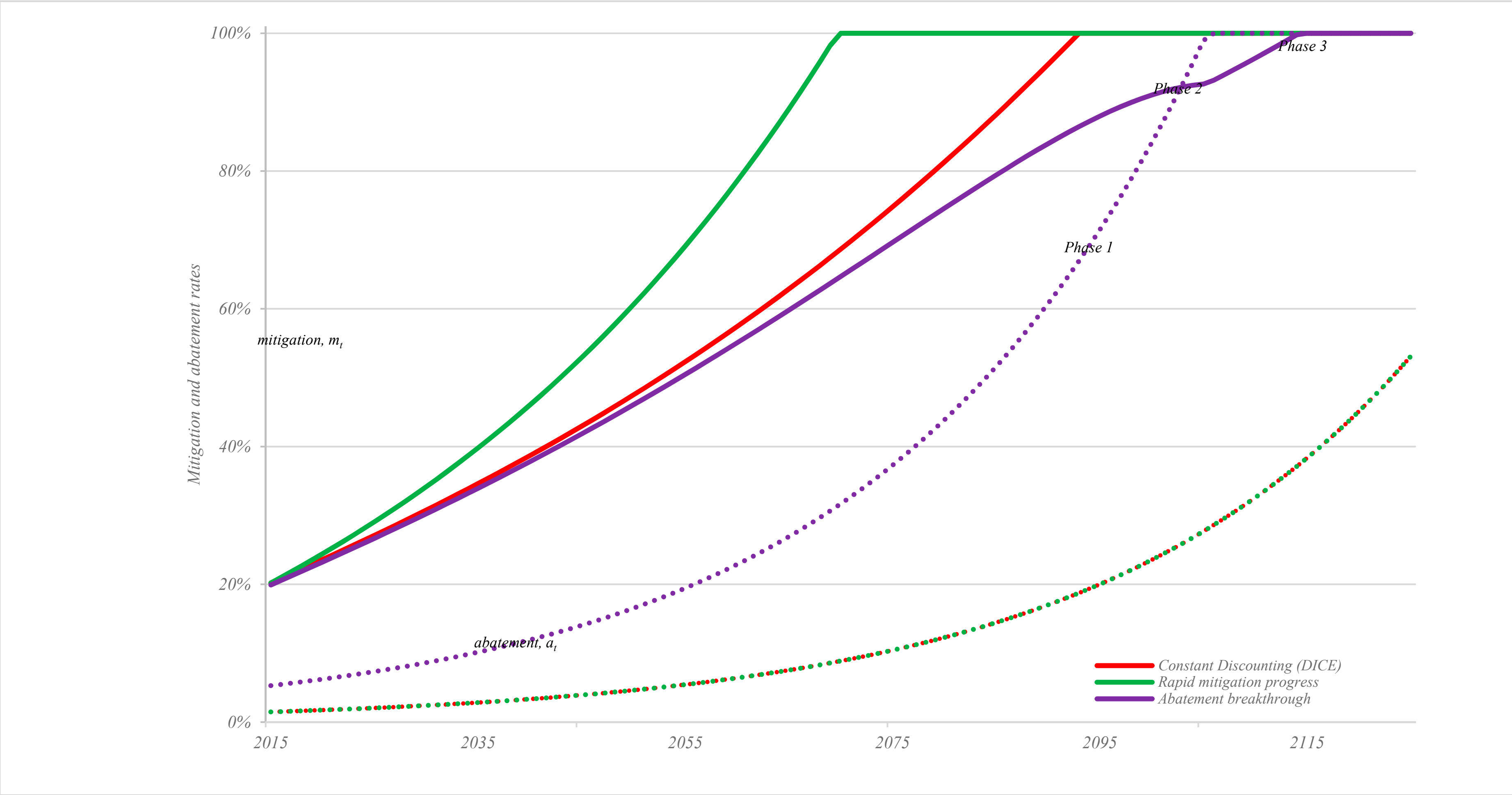
What is future is discounted less heavily in the distant future?

	Carbon price P_0	Abatement a_0	Mitigation m_0	Carbon budget B	End fossil era	Peak warming
Exponential discounting (DICE)	44 $/tC	1.5%	20%	635 GtC	78 yrs	2.6°C
Hyperbolic discounting (no commitment)	92 $/tC	3.1%	30%	362 GtC	63 yrs	2.0°C
Hyperbolic discounting (with commitment)	92 $/tC	3.1%	30%	320 GtC	59 yrs	1.9°C
Business as usual	0 $/tC	0%	0%	1,778 GtC	118 yrs	4.9°C
DICE	48 $/tC	–	17%	1,171 GtC	110 yrs	3.3°C

Ethical, economic and technological drivers of climate policy

	Carbon price P_o	Abatement a_o	Mitigation m_o	Carbon budget B	Peak warming PW
Constant discounting (DICE)	44 $/tC	1.5%	20.2%	635 GtC	2.6°C
Lower discounting	108 $/tC	3.7%	33.1%	314 GtC	1.9°C
Higher inequality aversion	28 $/tC	1.0%	15.9%	815 GtC	2.9°C
Slower economic growth	55 $/tC	1.9%	22.9%	534 GtC	2.4°C
Higher damage	87 $/tC	3.0%	29.5%	381 GtC	2.1°C
Rapid mitigation progress	44 $/tC	1.5%	20.2%	388 GtC	2.1°C
Abatement breakthrough	44 $/tC	5.3%	19.9%	595 GtC	2.5°C

Technological drivers of climate policy: abatement breakthrough leads to 100% CCS



Interpretation of 2 regimes

- Regime I (green and red lines): end of fossil fuel era (m = 1) before all fossil fuel is fully abated (a < 1) if technical progress in renewable energy production is fast compared with technical progress in abatement technology.

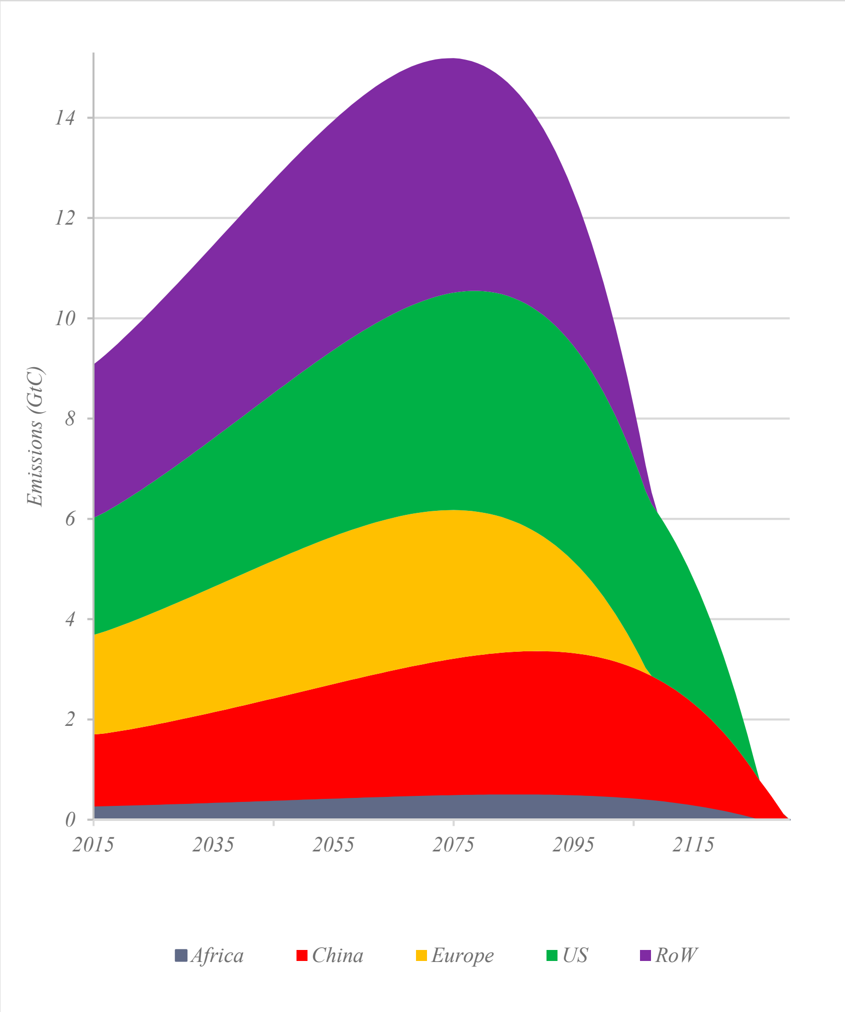
- Regime II (purple lines): fossil fuel is fully abated (a = 1) before all fossil fuel is replaced by renewable energies (so m < 1) otherwise, or if there is a massive breakthrough in abatement technology.

- Given current cost conditions and the ugly dynamics of NIMBY politics and running out of holes to put stuff in, the second regime seems less likely

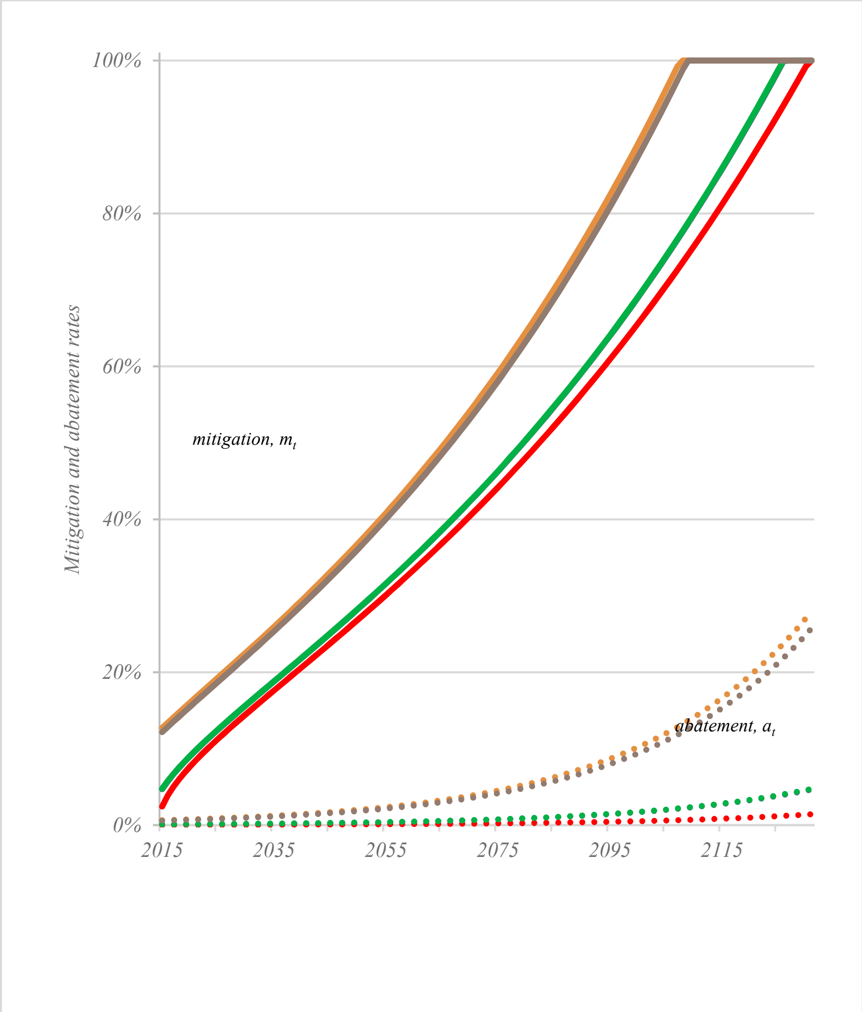
No international climate deal

- Business as usual is when none of the regions conduct climate policy.
- Non-cooperative outcome when none of the regions cooperate. Nash equilibrium then leads to lacklustre climate policies and more global warming.
- Cumulative emissions are much higher than under a climate deal, i.e., 1248 > 635 GtC. But lower than under BAU: 1246 < 1778 GtC.
- Of course, if there is no cooperation within each region, non-cooperative climate policies end up worse still and will be closer to BAU.
- Note: numbers are for exponential discounting. With hyperbolic discounting climate policy would be more ambitious as we have already seen.

Carbon emissions



Mitigation/abatement



Regional climate policy & global carbon budgets

Region	Carbon price P_0	Abatement a_0	Mitigation m_0	Carbon budget B
Africa	3.1 $/tC	0.1%	4.7%	43 GtC
China	1.0 $/tC	0.0%	2.4%	249 GtC
Europe	18.9 $/tC	0.6%	12.7%	224 GtC
US	3.2 $/tC	0.1%	4.8%	377 GtC
Rest of the World (RoW)	17.4 $/tC	0.6%	12.2%	355 GtC
Global cooperative	44 $/tC	1.5%	20.2%	635 GtC
Global non-cooperative **Business as usual**	11 $/tC 0 $/tC	0.4% 0%	8.8% 0%	1,248 GtC 1,178 GtC

Conclusions

- With DICE calibration with discount rate of 1.5% and *IIA* = 1.45 the optimal price of carbon is 44$/tC so carbon budget is 635 GtC and peak warming is 2.6 degrees.
- Price of carbon rises to 146$/tC with the Stern discount rate of 0.1%. Our hybrid case gives 92$/tC and limits global warming to 2 degrees with carbon budget of 362GtC! If policy makers can commit to their future selves budget would be 320 GtC as price of carbon would rise faster than 2% per year.
- If there is no climate deal, cumulative emissions are 1778 GtC and temperature rises to 4.9 degrees. Fossil fuel era ends in about 120 instead of 60 years. But China and US ratified Paris ....
- With regional cooperation but no international cooperation the carbon price are much less and thus mitigation and abatement are much less. In that case, a tough climate club with strong external punishments (5% trade tariff) would set in motion a dynamic that leads to increased membership (Nordhaus).

Second-best issues

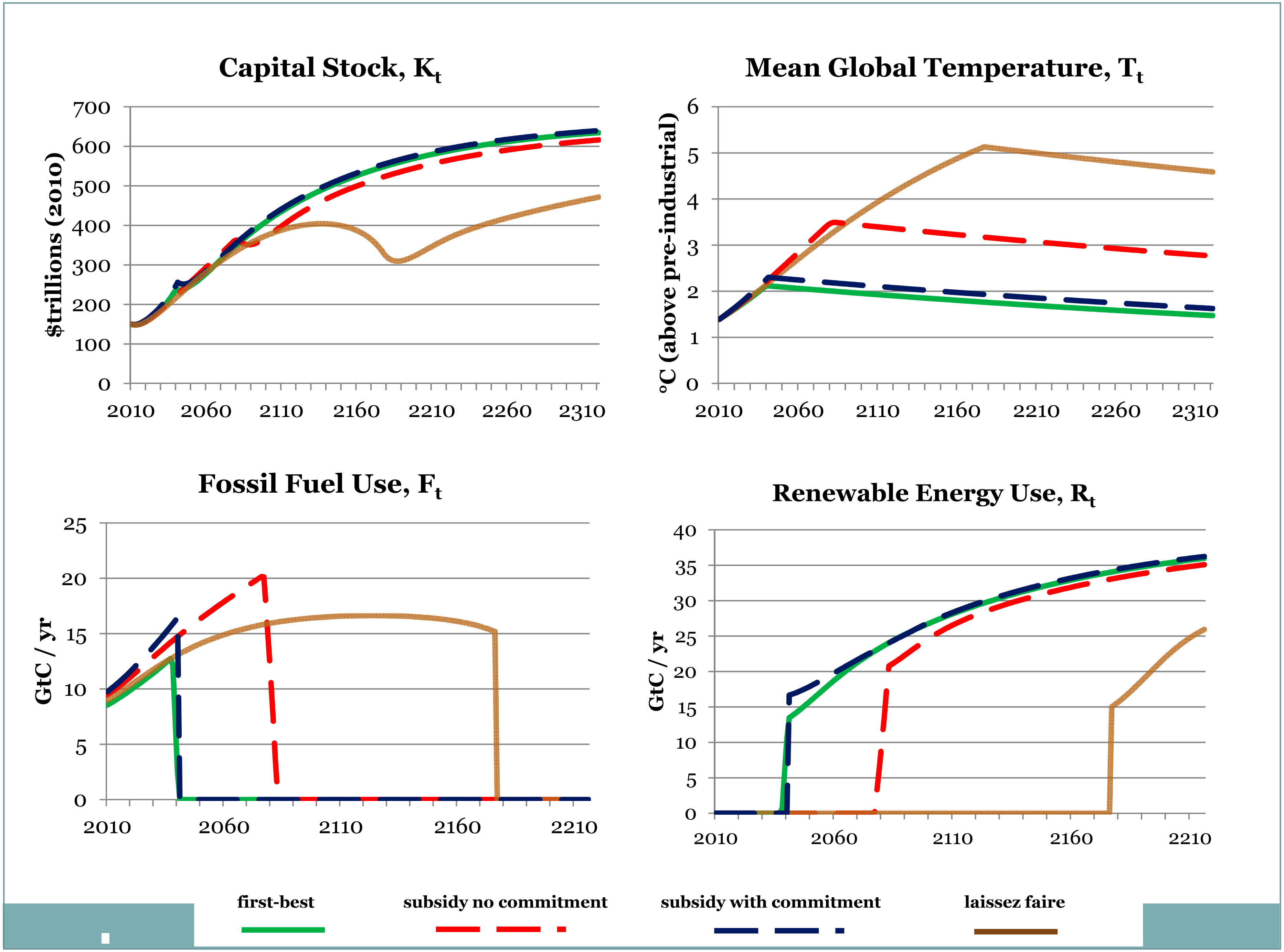
- If countries postpone carbon taxation, fossil fuel producers will accelerate extraction and thus accelerate carbon emissions. These adverse short-run effects are called the Green Paradox.
- But postponed carbon taxation also locks up more carbon and thus boosts welfare. Net effect on welfare is positive if supply reacts strongly to prices and demand does not and if the discount rate is small.
- Such second-best policies are time inconsistent.
- Same Green Paradox effects arise if governments prefer the carrot to the stick and subsidise renewable energies excessively to compensate for lack of carbon pricing.

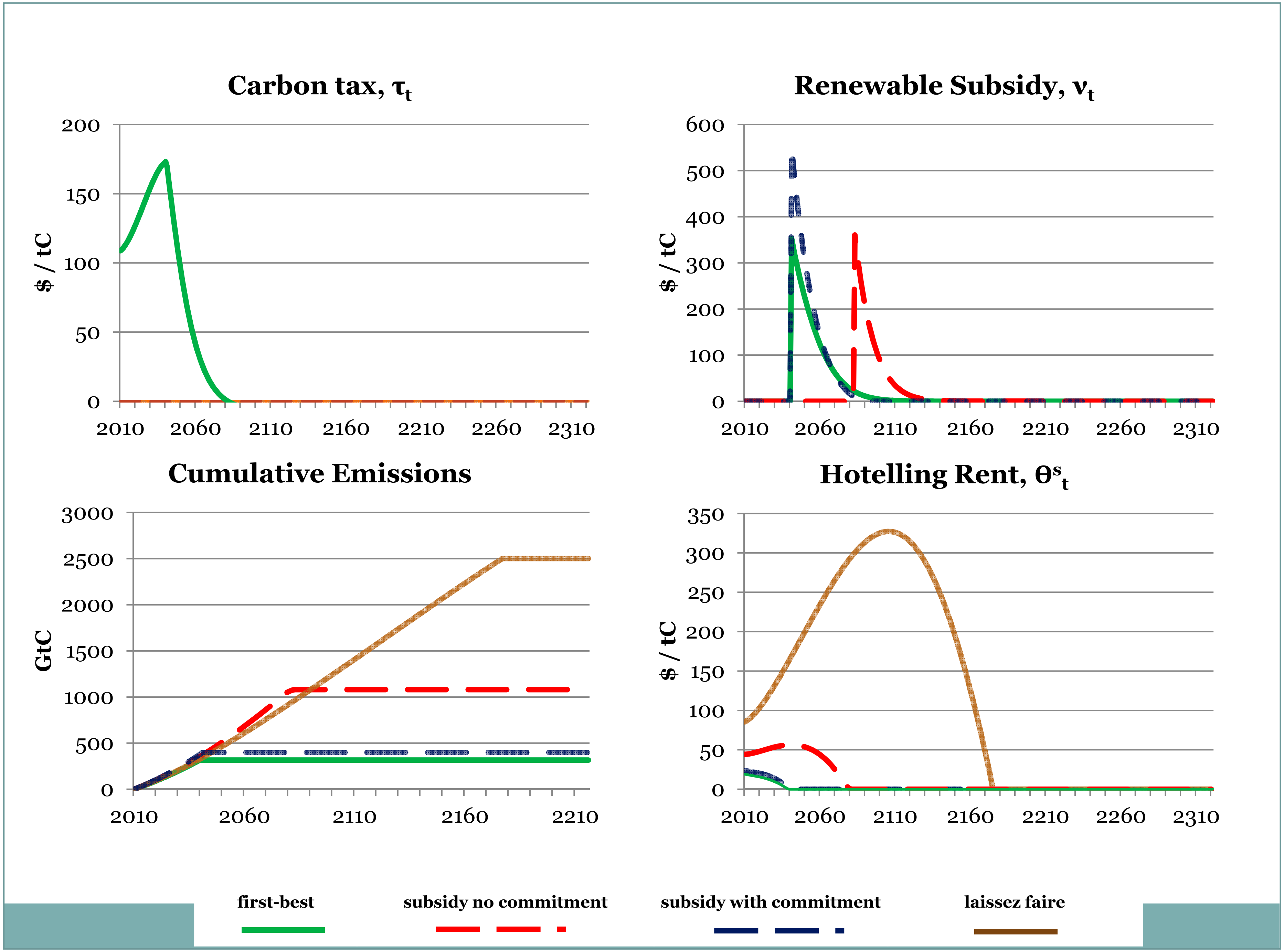
Second-best policy: 2 market failures

- In a second-best setting, the government misses at least one instrument. In our case, the tax is not feasible ($\tau_t = 0$) and the government has to choose how to maximize welfare choosing a subsidy, while respecting the decentralised market conditions.
- Under pre-commitment, the government increases the subsidy beyond the *SBL* in order to price fossil fuels out of the market.
- Under no-commitment (Markov Perfection), the government will set the subsidy to the *SBL* (i.e. it cannot use the subsidy to correct for the zero-tax.

Policy simulations

- Solution decade by decade from 2010 to 2600: t = 1 is 2010-2020, .., t = 60 is 2600-2610.
- I. the first-best outcome where the carbon tax is set to the optimal SCC, and the renewable subsidy to the optimal SBL, (solid green lines);
- II. the second-best case: subsidy without commitment (dashed blue lines);
- III. the second-best case: subsidy with pre-commitment (dashed red lines);
- IV. business as usual (BAU) without any policy (solid brown lines).


Capital Stock, K_t
$trillions (2010)
700
600
500
400
300
200
100
0
2010
2060
2110
2160
2210
2260
2310
Mean Global Temperature, T_t
°C (above pre-industrial)
6
5
4
3
2
1
0
2010
2060
2110
2160
2210
2260
2310
Fossil Fuel Use, F_t
GtC / yr
25
20
15
10
5
0
2010
2060
2110
2160
2210
Renewable Energy Use, R_t
GtC / yr
40
35
30
25
20
15
10
5
0
2010
2060
2110
2160
2210
first-best
subsidy no commitment
subsidy with commitment
laissez faire


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

- The optimal policy mix combines a persistent carbon tax with an aggressive renewable subsidy and limits warming to 2.1°C.
- Under laissez-faire, global temperature 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 a subsidy policy, the second-best subsidy can get close to the first-best outcome. There is a weak Green Paradox effect with small increase in temperature.
- If the government cannot commit to the 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

Finally, risk of stranded carbon assets

- To keep global warming below 2 degrees Celsius the world can only burn a couple of hundred GtC.
- Reserves of the big oil and gas companies are much bigger and that is not counting reserves of the state companies. Furthermore, there is a lot of new investment in fossil fuel including shale gas.
- If climate policy is going to be credible, there is a serious risk of stranded fossil fuel assets and one may as well short the oil and gas majors.
- What should for gas-exporting countries like Russia, Nigeria or Algeria do? Race to burn the last ton of carbon? (Limit pricing?)
- In any case, ongoing explosion of carbon discoveries and reserves cannot go on if planetary warming has to stay below 2 degrees Celsius. Need carbon pricing and climate club.

2 degrees Celsius target & stranded carbon assets

Keep 1/3 of oil (Canada, Arctic), 50% of gas & 80% of coal (mainly China, Russia, US) reserves unburnt. Reserves 3x and resources 10-11x the carbon budget. In Middle East 260 billion barrels of oil cannot be burnt. McGlade and Ekins (2015, Nature)