Integrated Policy Assessment in the Context of Global Warming

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May 25, 2010

Current Policy Debates

The role of renewable energy subsidies in the context of carbon pricing

- Should renewable energy be subsidized ?
  - No – *price only crowd* (Sinn, Nordhaus)
  - Yes – *hybrid crowd* (Acemoglou)
- Can renewable subsidies replace a carbon price?
- Can renewable subsidies improve a delayed carbon pricing policy?
- Can resource taxes and renewable energy subsidies provoke a green paradox?

Integrated policy assessment model (IPAM) to answer these questions

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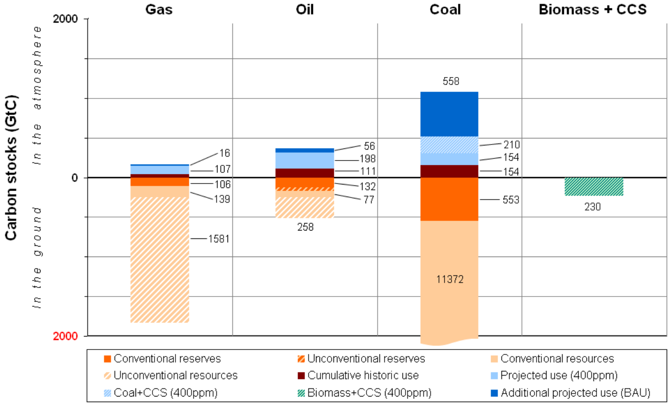
Outline

Carbon Budget Approach (Meinshausen et al. 2009)

- Probability of limiting global warming to 2K depends on cumulative 2000 – 2050 emissions
- $p > 50\%$: cumulative emissions $\leq 390 GtC$
- $p > 75\%$: cumulative emissions $\leq 270 GtC$



(Kalkuhl et al. 2010)

Model Design

Two exhaustible stocks (fossil resources, carbon budget)

- Distribution of rents
- Transition pathways beyond steady state (numerical model)

Consider intertemporal incentive structure

- Dynamic Stackelberg game: Government as Stackelberg Leader
- Irreversible investments

Multiple and 2nd-best policy instruments

- Decentralized general equilibrium model

Induced technological change

- Endogenous growth model (learning curves)

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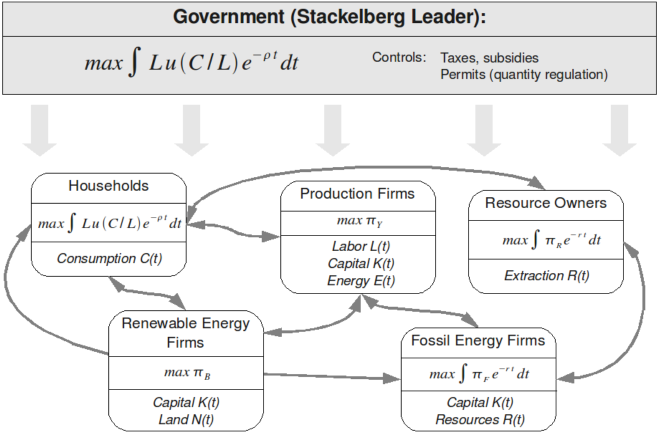
Game-theoretic Structure



Government's Optimization Problem (Stackelberg leader)

Objective:

$$\max_{\{\tau_i, P\}} \int_0^T L\ u\,(C/L)\, e^{-\rho t} dt \tag{1}$$

Constraints:

- *Political*: mitigation target
- *Technological*: production technologies
- *Strategical*: reaction functions of followers: analytic first-order conditions from intertemporal optimization

Control variables / policy instruments:

- Price instruments: taxes and subsidies $\{\tau_i\}$ on factor prices
- Quantity instruments: permits P

Policy Instruments

Price instruments

- Ad-valorem and unit taxes on factor prices for capital, labor, energy and resources
- E.g. net resource price for resource owners and net price for renewable energy read:

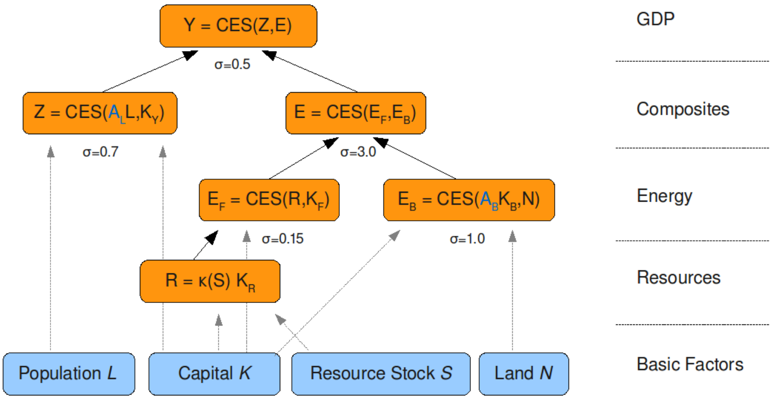
$$\bar{p}_R = p_R - \tau_R \quad (2)$$
$$\bar{p}_B = p_B(1 - \tau_B) \quad (3)$$

Quantity instrument / carbon bank

- Restrict emissions for economy through permits P
- Allow for intertemporal trading of permits

Government runs clear budget: tax incomes and subsidy expenditures are compensated by lump-sum transfers

Production Technologies



Technological Change

Endogenous Learning-by-Doing (Romer 1986):

- Investments into firm's capital stock K^i increase sector-wide factor productivity $A = A\left(\sum K^i\right)$
- Individual firms do not anticipate this effect, i.e. $\frac{\partial A}{\partial K^i} = 0$ (underinvestment)

Learning curve in renewable energy sector (leans on Kverndokk & Rosendahl 2007):

$$A_B = \frac{A_{max}}{1 + \left(\frac{\Omega}{K_B}\right)^{\gamma}} \tag{4}$$

Labor productivity: declining growth rate (exogenously)

$$\hat{A}_L = \frac{g}{e^{\zeta t} - g} \tag{5}$$

Households (1)

Objective:

$$\max_{\{C\}} \quad \int_0^T L\ u\left(C/L\right) e^{-\rho t} dt \tag{6}$$

Constraints:

$$u = \frac{\left(\frac{C}{L}\right)^{1-\eta}}{1-\eta} \tag{7}$$

$$C = wL + rK - I + \Pi + \Gamma \tag{8}$$

$$K = \sum_j K_j \quad I = \sum_j I_j \quad \Pi = \sum_j \Pi_j \tag{9}$$

$$\dot{K} = I - \delta K \tag{10}$$

$$K(0) = K_0 \tag{11}$$

Γ = lump-sum tax; Π_j = sectoral profits

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Households (2)

Hamiltonian:

$$H = L\ u(C/L) + \lambda_H(wL + rK - C + \Pi + \Gamma - \delta K) \tag{12}$$

First-order and transversality conditions:

$$\frac{\partial u}{\partial C} = \lambda_H \tag{13}$$

$$\dot{\lambda}_H = \lambda_H(\rho + \delta - r) \tag{14}$$

$$0 = \lambda_H(T)K(T) \tag{15}$$

Ramsey-rule:

$$r - \delta = \rho + \eta \hat{C} \tag{16}$$

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Resource Sector (1)

Objective:

$$\max_{\{K_R\}} \int_0^\infty \Pi_R \; e^{-\int_0^t (r-\delta)\; ds} dt \tag{17}$$

Constraints:

$$\Pi_R = (p_R - \tau_R) R(S, K_R) - r K_R \tag{18}$$

$$R = \kappa(S) K_R \tag{19}$$

$$\kappa(S) = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S}{\chi_3} \right)^{\chi_4}} \tag{20}$$

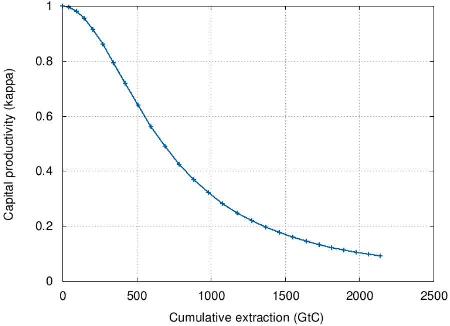
$$\dot{S} = -R \tag{21}$$

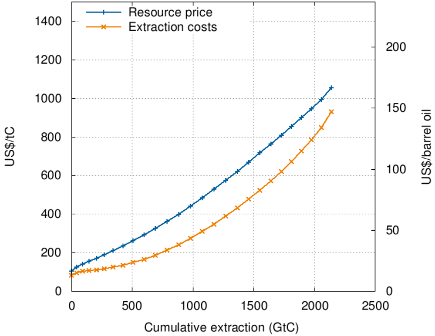
$$S(0) = S_0 \tag{22}$$

Rogner Curve

Productivity of capital κ decreases with cumulative extraction $S_0 - S$:

$$\kappa(S) = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S}{\chi_3}\right)^{\chi_4}} \quad , \quad \frac{\partial \kappa(S)}{\partial S} > 0 \qquad (23)$$





Resource Sector (2)

Hamiltonian:

$$H_R = (p_R - \tau_R)\kappa K_R - rK_R - \lambda_R \kappa K_R \quad (24)$$

First-order and transversality conditions:

$$\lambda_S = p_R - \tau_R - r/\kappa \quad (25)$$

$$\dot{\lambda}_S = (r - \delta)\lambda_S - (p_R - \tau_R - \lambda_S)K_R \frac{\partial \kappa}{\partial S} \quad (26)$$

$$0 = \lambda_S(T)S(T) \quad (27)$$

Production Sector

Objective and constraints:

$$\Pi_Y = Y(K_Y, L, E_F, E_B) - rK_Y - wL - p_F E_F - p_B E_B \tag{28}$$

$$Y = \left(a_1 Z^{\frac{\sigma_1 - 1}{\sigma_1}} + b_1 E^{\frac{\sigma_1 - 1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1 - 1}} \tag{29}$$

$$Z = \left(a_2 {K_Y}^{\frac{\sigma_2 - 1}{\sigma_2}} + b_2 (A_L L)^{\frac{\sigma_2 - 1}{\sigma_2}}\right)^{\frac{\sigma_2}{\sigma_2 - 1}} \tag{30}$$

$$E = \left(a_3 {E_F}^{\frac{\sigma_3 - 1}{\sigma_3}} + b_3 {E_B}^{\frac{\sigma_3 - 1}{\sigma_3}}\right)^{\frac{\sigma_3}{\sigma_3 - 1}} \tag{31}$$

First-order conditions:

$$r = \frac{\partial Y}{\partial K_Y}, \quad w = \frac{\partial Y}{\partial L}, \quad p_F = \frac{\partial Y}{\partial E_F}, \quad p_B = \frac{\partial Y}{\partial E_B} \tag{32}$$

Fossil Energy Sector (1)

Objective:

$$\max_{\{I_F,R\}} \quad \int_0^{\infty} \Pi_F \; e^{-\int_0^t (r-\delta) \; ds} dt \tag{33}$$

Constraints:

$$\Pi_F = p_F E_F(K_F, R) - rK_F - p_R R \tag{34}$$

$$E_F = \left(aK_F^{\frac{\sigma-1}{\sigma}} + (1-a)R^{\frac{\sigma-1}{\sigma}} \right)^{\left(\frac{\sigma}{\sigma-1}\right)} \tag{35}$$

Two model variants:

- Reversible investments possible: $I_F \in \mathbb{R}$ (reference model)
- Irreversible investment dynamics: $I_F \geq 0$

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Fossil Energy Sector (2)

First-order and transversality conditions:

$$p_R = p_F \frac{\partial E_F}{\partial R} \tag{36}$$

$$\dot{\lambda}_F = (r - \delta)\lambda_F - \left[p_F \frac{\partial E_F}{\partial K_F} - r\right] \tag{37}$$

$$I_F \lambda_F = 0 \tag{38}$$

$$K_F(T)\lambda_F(T) = 0 \tag{39}$$

In the case of reversible investments, $\lambda_F \equiv 0$ and, thus:

$$p_R = p_F \frac{\partial E_F}{\partial R} \tag{40}$$

$$r = p_F \frac{\partial E_F}{\partial K_F} \tag{41}$$

Renewable Energy Sector

Objective and first-order conditions:

$$\Pi_B = p_B(1 - \tau_B)E_B - (r + v)K_B \quad (42)$$

$$E_B = A_B K_B^{\nu} N^{\nu-1} \quad (43)$$

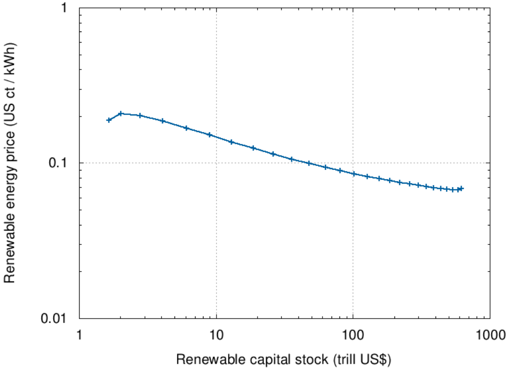
$$r = p_B \frac{\partial E_B}{\partial K_B} \quad (44)$$

where $\frac{\partial A_B}{\partial K_B} = 0$ from the single firm's point of view (learning-by-doing spillover)

From the economy-wide perspective, however, A_B increases with cumulative investment (capital stock K_B):

$$A_B = \frac{A_{max}}{1 + \left(\frac{\Omega}{K_B}\right)^{\gamma}} \quad (45)$$

Renewable Energy Learning Curve



$$A_B = \frac{A_{max}}{1+\left(\frac{\Omega}{K_B}\right)^{\gamma}}$$

Productivity of capital A_B increases with cumulative investment (capital stock K_B)

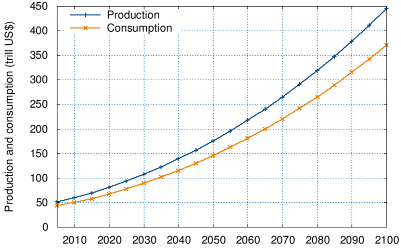
Calibration and Implementation

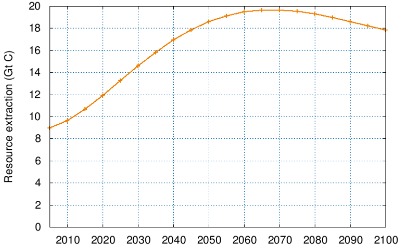
Calibration:

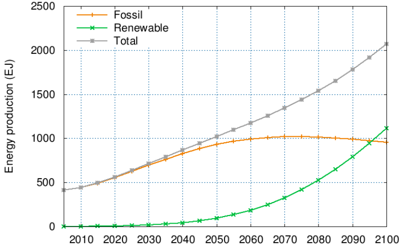
- Model results grossly harmonized with ReMIND results and parameters from literature (e.g. elasticities of substitution)
- Carbon budget: 450 GtC for fossil resources
- Time horizon: 2005-2150 for optimization; 2005-2100 for evaluation
- Population: increase up to 9.5 billion
- Mitigation costs: 1.9 % GDP losses; 2.9 % consumption losses

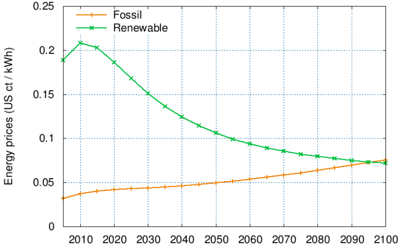
Elasticities of substitution		**Utility function**	
Capital-Labor	0.70	STPR ρ	0.03
Composite-Energy	0.50	EIS η	1.00
Fossil-Renewable	3.00		
Capital-Resources	0.15	**Initial values**	
Capital-Land	1.00	K_0 (trill USD)	98.69
Depreciation δ	0.03	S_0 (GtC)	4,000

Business-as-usual Scenario









Carbon Pricing within the Carbon-Budget Approach

Why do we observe a Hotelling carbon price?

- Optimal carbon price within cost-benefit analysis (Hoel and Kverndokk 1996):

$$\tau_R = \int_t^\infty -d_S(S(\xi))e^{r(t-\xi)}\, d\xi$$

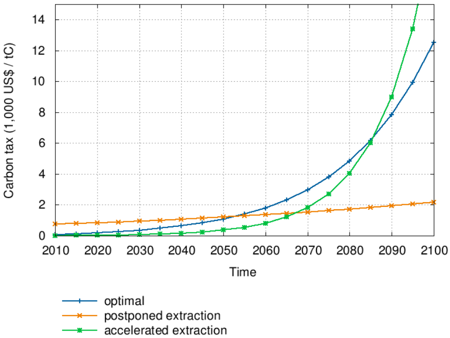
- Carbon budget is a politically created exhaustible resource
- Optimal carbon tax is a Hotelling scarcity price (Kalkuhl and Edenhofer 2010):

$$\tau_R = \tau_0 e^{rt}$$

- Free permit trading also leads to Hotelling price (Kling and Rubin 1996)
- Carbon-Budget Approach does not achieve an intertemporally efficient allocation of climate damages

Is a Carbon Tax a Robust Policy Instrument?

- Regulator imposes exponentially increasing ad-hoc carbon tax: $\tau = \tau_0 e^{\theta t}$
- Fast increasing tax ($\tau_0 = 10, \theta = 0.08$): Accelerated extraction
- Slow increasing tax ($\tau_0 = 700, \theta = 0.01$): Postponed extraction
- Acceleration possible for fast increasing tax (Sinn 2010, Edenhofer & Kalkuhl 2010)



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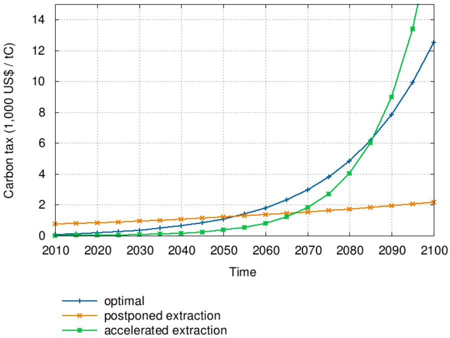
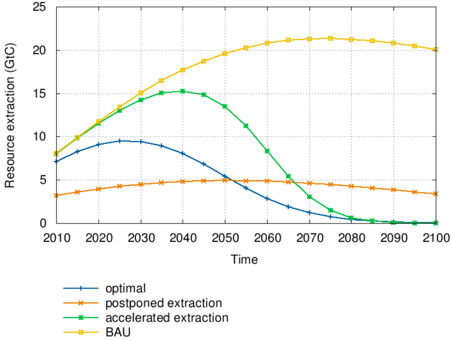




Is a Carbon Tax a Robust Policy Instrument?

- Sinn (2008): increasing ad-valorem taxes lead to accelerated resource extraction
- Edenhofer & Kalkuhl (2010): increasing unit tax $\tau = \tau_0 e^{\theta t}$ on carbon
- Green paradox does only occur for critical (τ_0, θ) in Hotelling model with constant extraction costs:

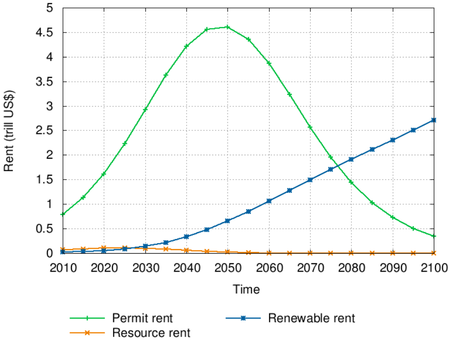
	Slowly increasing tax $\theta < r$		**Tax increases at discount rate** $\theta = r$		**Fast increasing tax** $\theta > r$	
	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$
Timing effect	postpone extraction	postpone extraction	none	none	accelerate extraction	accelerate extraction
Volume effect	none	conservative	none	conservative	none	conservative
Green paradox	none	none	none	none	yes	ambiguous
Impact on damages compared to zero-tax case	- timing effect	-- timing and volume effect	none	- volume effect	++ timing effect	-/+ timing vs. volume effect

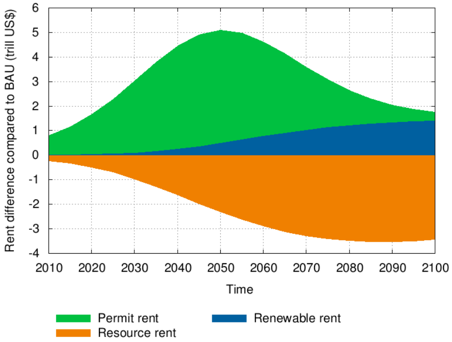
Critical initial tax level τ_0^* such that $S_0 = \int_0^\infty D\left(\tau_0^* e^{\theta t} + c\right)\ dt$.

Mitigation Changes Rents

Mitigation changes scarcity rents:

1. Fossil resource rent is reduced
2. Renewable (land) rent increases
3. Permit (carbon budget) rent increases





Renewable Energy Market Failures

1. Learning curves suffer from spillovers of experience between firms

- Not all innovations can be protected by patents
- Patent runtime may be suboptimal
- Network externalities imply economy of scale

Pigovian spillover subsidy (for 100 % spillover rate of learning curve)

$$\tau_B = -\frac{\gamma}{\nu + \nu \left(\frac{K_B(t)}{\Omega}\right)^{\gamma}} \tag{46}$$

For increasing capacity, subsidy decreases in the long run:

$$\lim_{K_B \to \infty} \tau_B = 0$$

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2. Renewable energy sector pays risk premium v at the capital market

- Small and medium-size firms suffer from liquidity constraints and capital market imperfections (e.g. Hubbard 1998)
- Investors have lower confidence in newcomer firms
- Competitiveness of renewable energy depends on political regulation – regulatory uncertainty requires higher risk premium

Few systematic data available for energy sector (which is already highly distorted by regulation), but some illustrative numbers:

- RWE's cost of debt (2008): 5.25 %
- DESERTEC's cost of debt: 8 %

Ad-hoc assumption for risk premium: $v = 5\%$ in year 2005 and decrease by 1 percentage point per decade.

Pigovian subsidy for suboptimal risk premium: $\tau_B = -\frac{v}{r}$
Considerable subsidy rates may be necessary: if $v \approx r$, $\tau_B \approx -1$.

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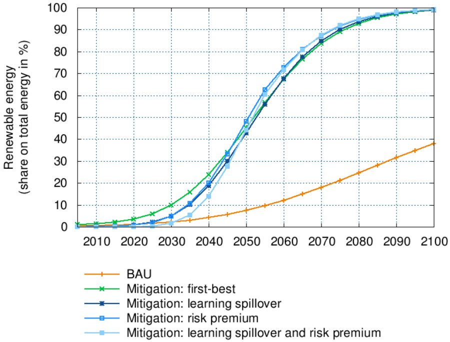


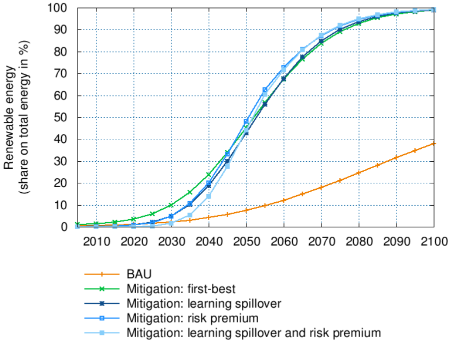
Renewable energy production for several market imperfections:

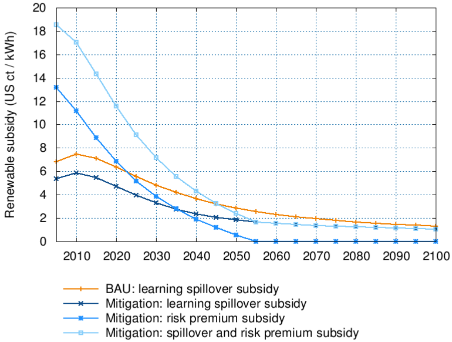
- Only small deviations from 1st-best
- Renewable energy is most important mitigation option

Optimal renewable energy subsidies:

- BAU requires higher spillover subsidy
- Significant subsidies necessary

Renewable Energy Market Failures





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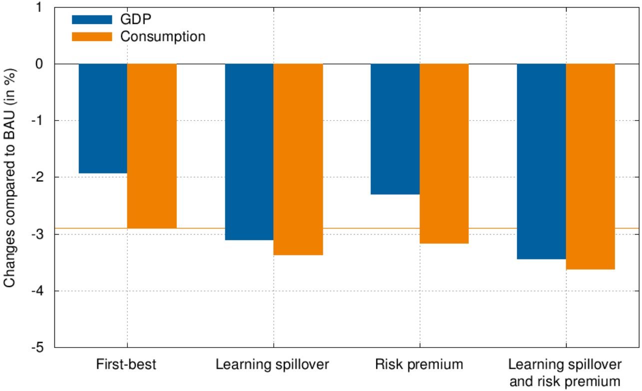
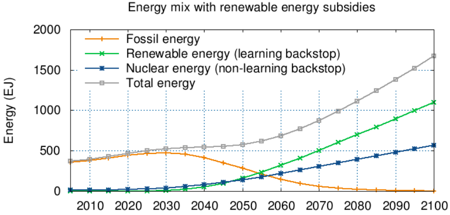


Figure: GDP and consumption losses of mitigation if renewable energy sector suffers from uncorrected learning spillovers and capital risk premiums.

Extension: Learning and Non-learning Technologies

Introduce non-learning backstop energy (i.e. nuclear): $E_N = A_N K_N$



1st-best energy mix:

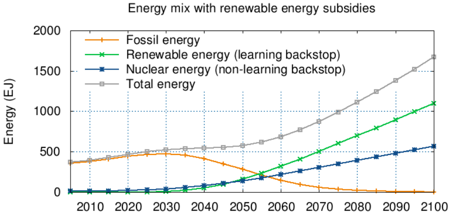
- In the short term: high-cost backstop is cheaper than learning backstop
- In the long term: learning backstop dominates

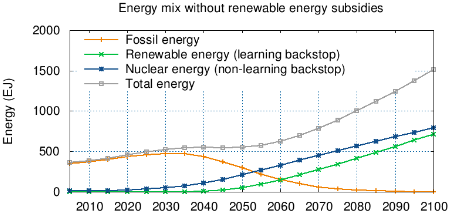
No renewable energy subsidies:

- Nuclear energy dominates
- No complete crowding out due to limited substitutability

Extension: Learning and Non-learning Technologies

Introduce non-learning backstop energy (i.e. nuclear): $E_N = A_N K_N$





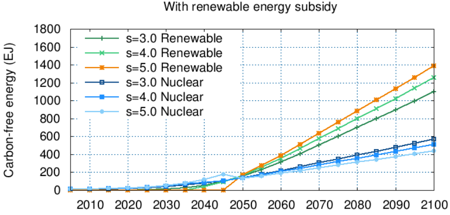
1st-best energy mix:

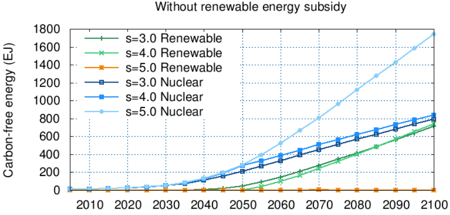
- In the short term: high-cost backstop is cheaper than learning backstop
- In the long term: learning backstop dominates

No renewable energy subsidies:

- Nuclear energy dominates
- No complete crowding out due to limited substitutability

Preliminary Results: Lock-in Effects





Critical parameter: Elasticity of substitution between learning and non-learning technology

- Higher elasticities lead to lock-in: No renewable energy production
- Lock-in causes high consumption losses

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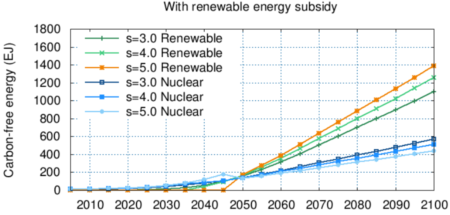

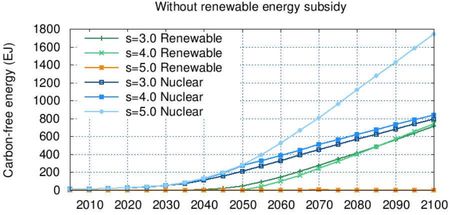

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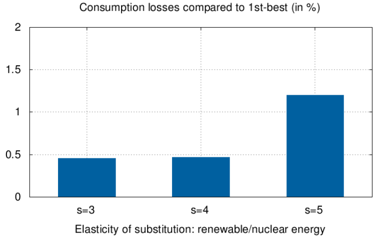

Imperfect Carbon Pricing

What is the role of renewable subsidies under imperfect carbon pricing?

1. Delayed carbon price: Global carbon price established from 2035 on
2. No carbon price feasible at all

Consider the following policy options for renewable energy sector:

- No additional subsidy
- Optimal 2nd-best subsidy

Modification in model structure

- Reversible ($I_E \in \mathbb{R}$) and irreversible ($I_E \geq 0$) investments in fossil energy sector
- Suppress other externalities (no learning spillovers; no investment risk premium)

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Imperfect Carbon Pricing: Supply-side Dynamics

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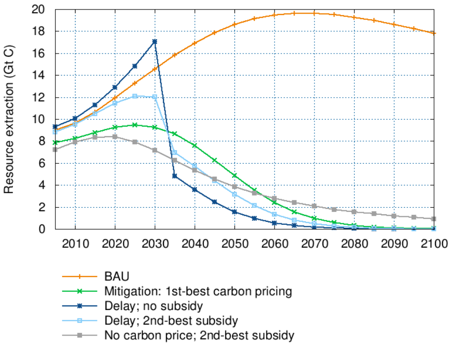

Accelerated extraction (green paradox) when delayed carbon price is anticipated

Early extraction reduction (from 2020 on) when investments are irreversible and future carbon price is anticipated

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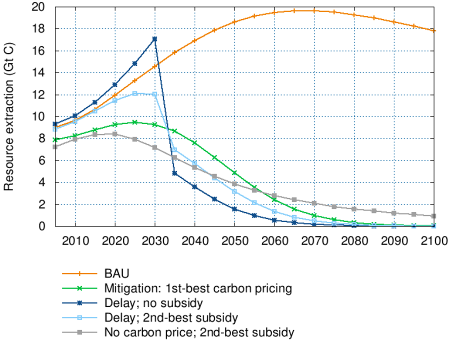

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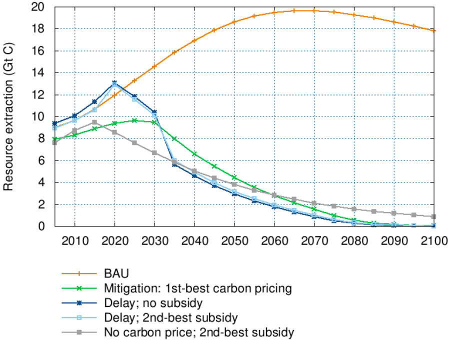

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Imperfect Carbon Pricing: Consumption Losses

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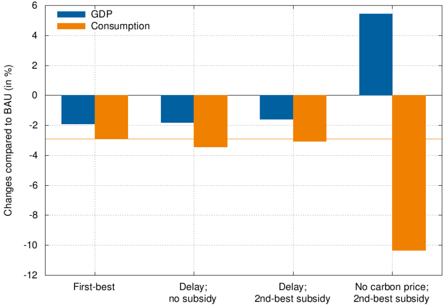

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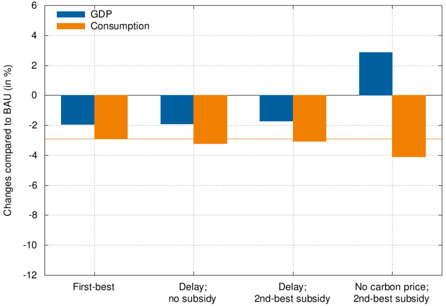
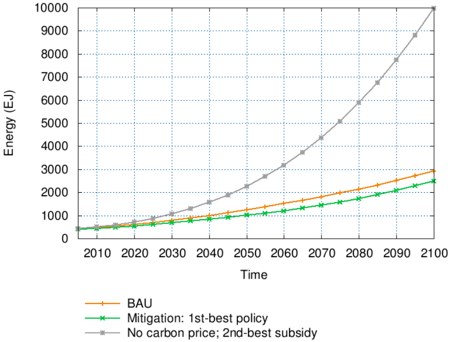


Investment inertia lowers mitigation costs:

- Delayed carbon price (without subsidy): From 3.4% to 3.2%
- Delayed carbon price (2nd-best subsidy): From 3.1% to 3.0%
- No carbon price: From 10.3% to 4.1%

Imperfect Carbon Pricing: The Rebound Effect

- Renewable subsidies imply higher energy demand
- Green growth due to cheap (subsidized) renewable energy: +5.4%
- High consumption losses (GDP used for renewable energy production): −10.3%



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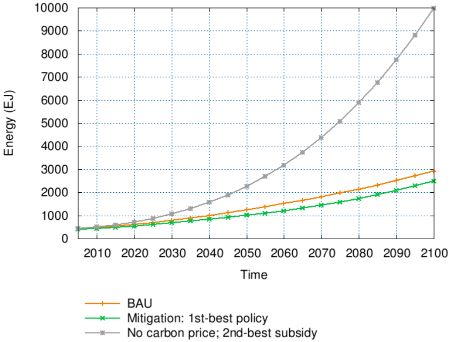

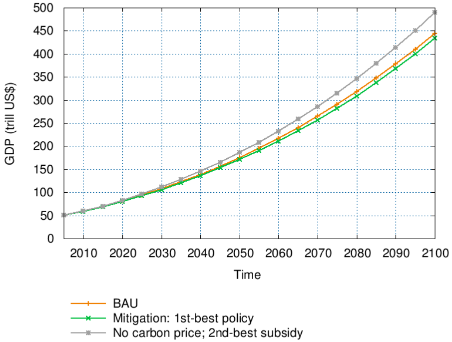

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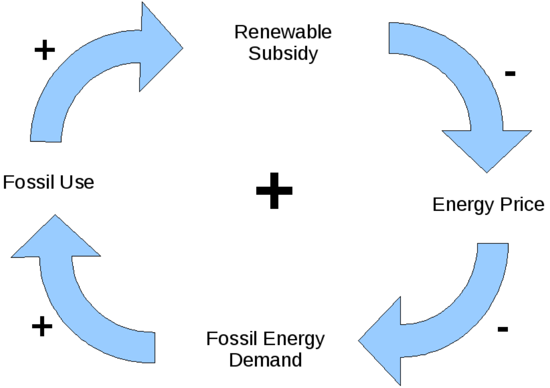
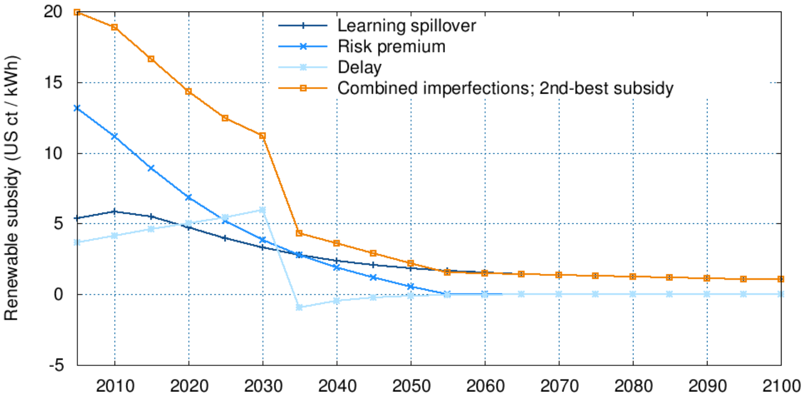


Isolated vs. Multiple Imperfections



Multiple-market-failure subsidy is lower than the sum of isolated-market-failure subsidy.

Isolated vs. Multiple Imperfections

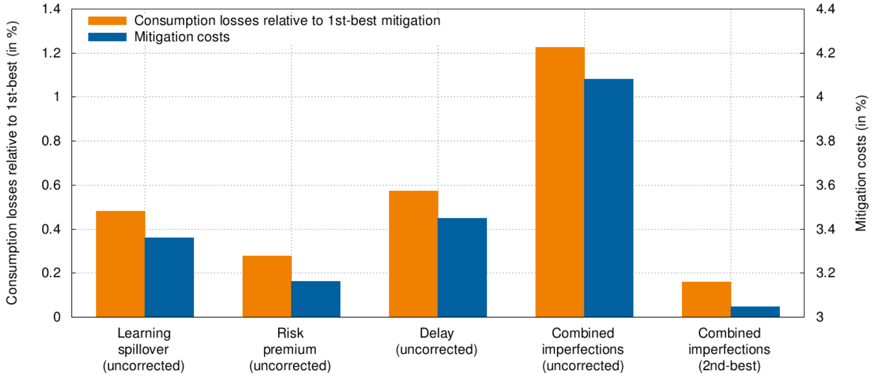


Figure: Consumption losses for isolated and combined imperfections

Summary

Optimal policy instruments

- Carbon price (tax or permit) – increasing with interest rate
- Learning-curve spillover subsidies – declining with capacity building
- Investment risk subsidy – diminishing with time

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  - Explore lock-in possibilities (parameter studies)
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Thank You for Your Attention!

For further questions contact:

Matthias Kalkuhl: kalkuhl@pik-potsdam.de
Ottmar Edenhofer: edenhofer@pik-potsdam.de

Potsdam Institute for Climate Impact Research.
Potsdam, Germany.

PIK

Backup Slides

Imperfect Carbon Pricing: Subsidies and Carbon Prices

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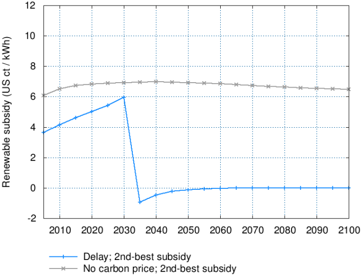

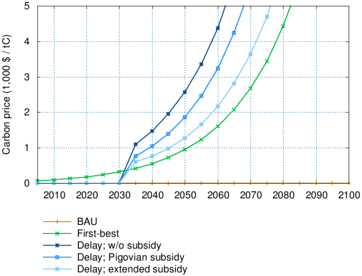

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