System of Innovation and Inertia: A mathematical exploration with implications for climate change abatement

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Key Questions

Classical cost-benefit analysis framework & marginal abatement cost curves (MACCs) to analyse optimal abatement trajectories.

- Inertia – Adaptability
- Long-lived energy infrastructure
- Path Dependency

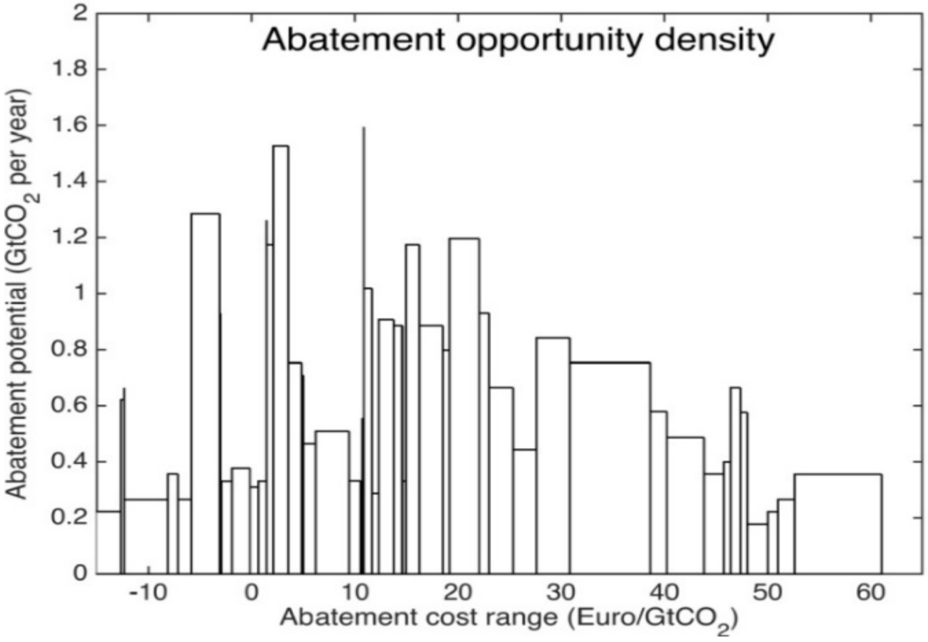
Low-carbon **investment**

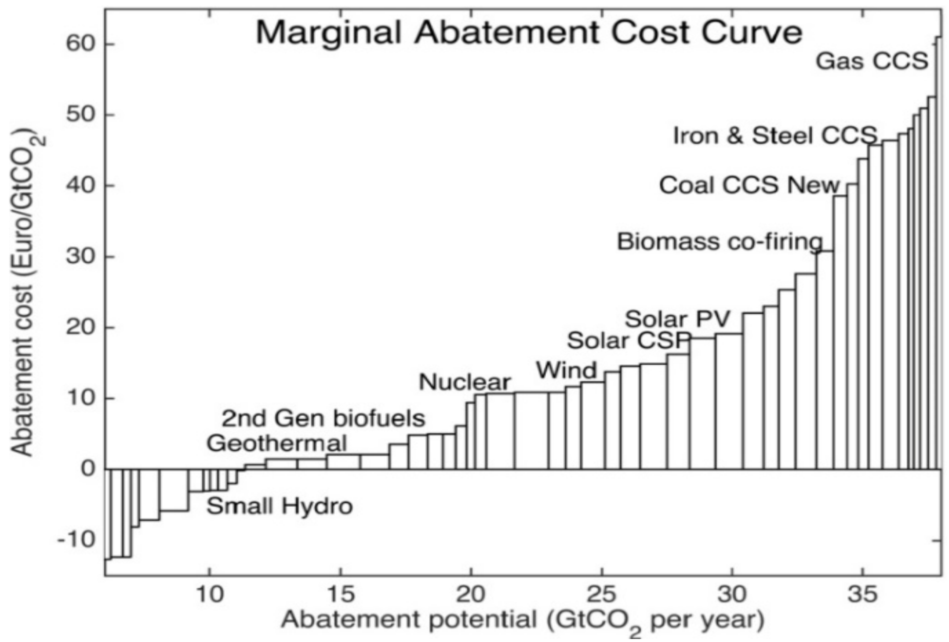
Low-carbon **technology**

Low-carbon **supply chain**

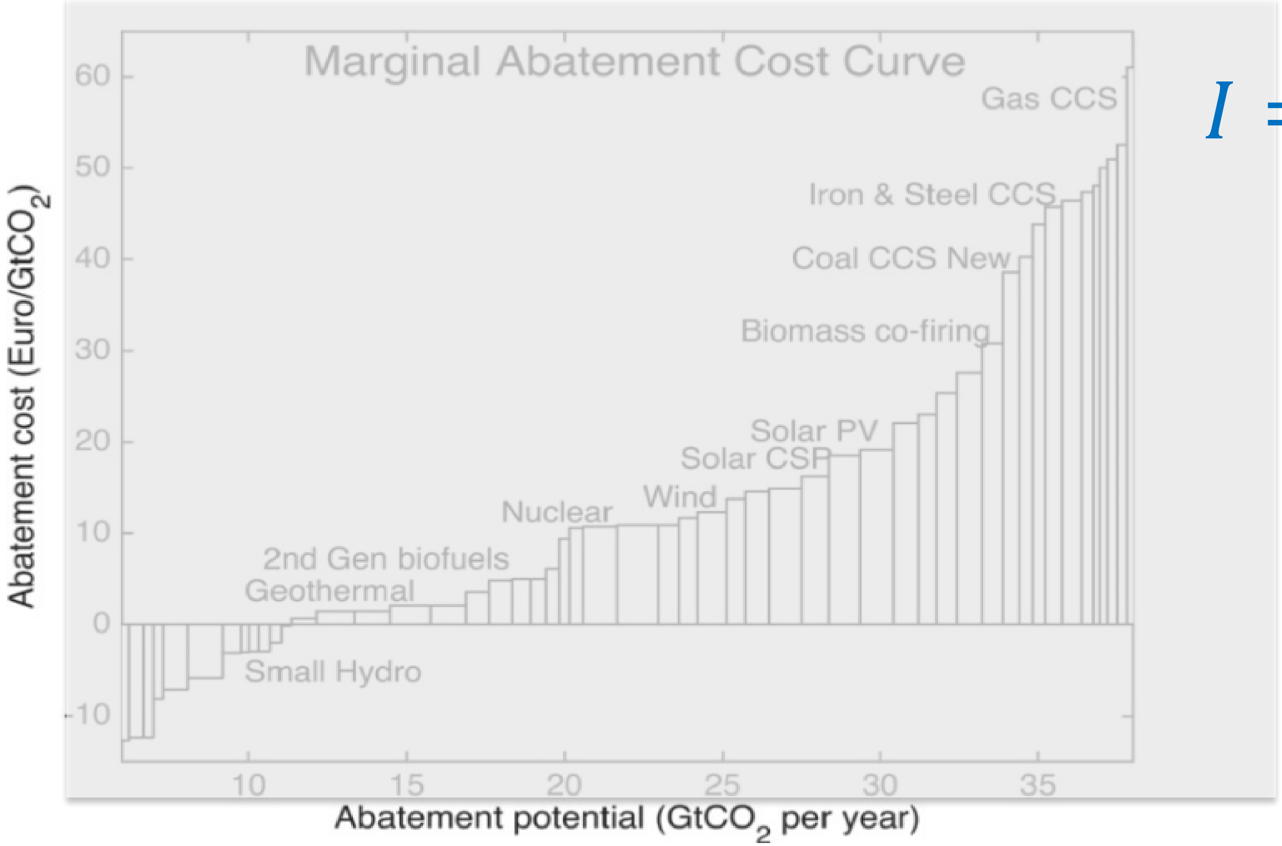
The **speed** of decarbonisation is relevant

Marginal Abatement Cost Curves MACCs





Marginal Abatement Cost Curves MACCs



$$I = \alpha_A \varepsilon^{\gamma}$$

Marginal Abatement Cost Curves MACCs

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$$\varepsilon_{k-1} \quad \varepsilon_k$$

$$\approx \beta U_k$$

Marginal Abatement Cost Curves MACCs

$$\int_0^{\mathrm{U_k}} \mathrm{I_k}(U)\,d\mathrm{U} = \int_{\varepsilon_{k-1}}^{\varepsilon_k} \mathrm{I_k}(\varepsilon)\frac{d\varepsilon}{\beta}$$

$$I = \alpha_A \varepsilon^{\gamma}$$

$$\varepsilon_{k-1} \quad \varepsilon_k$$

$$\approx \beta U_k$$

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‘Classical’ (Enduring) Abatement Cost

Following the MACC approach, the abatement cost is summed over all the sectors. For tractability purposes, measures are assumed to be implemented in order of cost:

$$c_A = \sum_{\mathrm{k}} \int_0^{\mathrm{U_k}} \mathrm{I_k}(U)\, d\mathrm{U} = \sum_{\mathrm{k}} \int_{\varepsilon_{\mathrm{k-1}}}^{\varepsilon_{\mathrm{k}}} \mathrm{I_k}(\varepsilon) \frac{d\varepsilon}{\beta} = \sum_{\mathrm{k}} \int_{\varepsilon_{\mathrm{k-1}}}^{\varepsilon_{\mathrm{k}}} \frac{\alpha_A \varepsilon^{\gamma}}{\beta} d\varepsilon$$

$$c_A = \frac{\alpha_A \varepsilon^{\gamma+1}}{(\gamma+1)\beta}$$

$$\Lambda(t) = \Psi(t)\, \theta_1(t)\, \mu(t)^{\theta_2}$$

Including learning on enduring abatement cost

Learning-by-doing can be represented by a decay in cost proportional to the increase in installed capacity

$$I_k(\mathrm{t}) = I_k^0 \left(\frac{W_k^0 + W_k(\mathrm{t})}{W_k^0}\right)^{-b_k} = I_k^0 \left(1 + \frac{\int_0^t \dot{U}_k(t')dt'}{W_k^0}\right)^{-b_k}$$

$$I_k(\mathrm{t}) = I_k^0 \left(1 + \frac{\int_0^t \dot{\varepsilon}_\mathrm{k}(t')dt'}{\beta_k W_k^0}\right)^{-b_k} = I_k^0 \left(1 + \frac{\varepsilon(\mathrm{t})}{\beta_k W_k^0}\right)^{-b_k}$$

Including learning (cont…)

Adding the cost over all the sectors:

$$c_A \approx \sum_k \int_0^{\mathrm{U_k}} \mathrm{I_k(U)}\,d\mathrm{U} = \sum_k \int_{\varepsilon_{k-1}}^{\varepsilon_k} I_k^0 \left(1 + \frac{\varepsilon}{\beta_k W_k^0}\right)^{-b_k} \frac{d\varepsilon}{\beta_k}$$

$$c_A \approx \sum_k \int_{\varepsilon_{k-1}}^{\varepsilon_k} \frac{\alpha_A \varepsilon^\gamma}{\beta} \left(1 + \frac{\varepsilon}{\theta}\right)^{-b_k} d\varepsilon \approx \frac{\alpha_A \theta^b}{(\gamma + 1 - b)\beta} \varepsilon^{\gamma+1-b}$$

Enduring Abatement Cost

Cost without learning: $$c_A = \frac{\alpha_A \varepsilon^{\gamma+1}}{(\gamma+1)\beta}$$

Cost with learning: $$c_A = \frac{\alpha_A \theta^b}{(\gamma+1-b)\beta} \varepsilon^{\gamma+1-b}$$

Cost in DICE: $$\Lambda = \Psi\theta_1\mu^{\theta_2} = \Psi\theta_1\mu^2$$

In the classical approach (Nordhaus' model DICE), abatement cost is proportional to the square of abatement, equivalent to have $\gamma = 1$ (linear MACC curve)

Adaptive Abatement Cost

To produce **wind power**, investment in **wind turbines** is required

Adaptive Abatement Cost

To produce **wind power**, investment in **wind turbines** is required... to produce **wind turbines**, investment in **wind turbine factories** is required

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Adaptive Abatement Cost

$$\int_0^{\mathrm{U_k}} \mathrm{I_k}(U)d\mathrm{U} \quad c_A = \alpha_A \varepsilon^{\gamma+1}$$

$$\int_0^{\dot{\mathrm{U}}_\mathrm{k}} \mathrm{I_k}(\dot{U})d\dot{\mathrm{U}} \quad c_B = \alpha_B \dot{\varepsilon}^{\gamma+1}$$

Adaptive Abatement Cost

Following the same approach, it is possible to build a MACC curve for **production capacity of abatement** $\dot{\varepsilon}$ rather than abatement ε itself:

$$I_A = \alpha_A \varepsilon^{\gamma}$$

$$I_B = \alpha_B \dot{\varepsilon}^{\gamma}$$

$$c_A = \frac{\alpha_A \varepsilon^{\gamma+1}}{(\gamma+1)\beta}$$

$$c_B = \frac{\alpha_B \dot{\varepsilon}^{\gamma+1}}{(\gamma+1)\tilde{\beta}}$$

$$c_A = \frac{\alpha_A \theta^{b}}{(\gamma+1-b)\beta} \varepsilon^{\gamma+1-b}$$

$$c_B = \frac{\alpha_B \tilde{\theta}^{\tilde{b}}}{(\gamma+1-\tilde{b})\tilde{\beta}} \dot{\varepsilon}^{\gamma+1-\tilde{b}}$$

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Higher Order Component

Sectors are interrelated to supply chain flows that can be represented, to first order, with the Leontief inverse of a static investment input-output matrix. Then, it can be easily demonstrated that building production capacity represents a cost that distributes across many sectors of the economy:

$$\boldsymbol{I}^{N}\dot{\varepsilon} = \boldsymbol{I}^{\boldsymbol{N0}}\dot{\varepsilon} + \boldsymbol{A}\boldsymbol{I}^{\boldsymbol{N0}}t_1\ddot{\varepsilon} + \boldsymbol{A}^2\boldsymbol{I}^{\boldsymbol{N0}}t_2\dddot{\varepsilon} + \boldsymbol{A}^3\boldsymbol{I}^{\boldsymbol{N0}}t_3\ddddot{\varepsilon} + \cdots$$

Summary of Abatement Costs

Cost Component	Simplified Expression	Dependence
Classical enduring abatement	$c_A = \tilde{\alpha}_A \varepsilon^{\gamma+1-b}$	Replacing emission sources
Adaptive abatement	$c_B = \tilde{\alpha}_B \dot{\varepsilon}^{\gamma+1-\tilde{b}}$	Transforming production capital
Early Scrapping	$c^{ES} = \alpha^{ES} \dot{\varepsilon}^2$	Forgone income from decommissioned emission sources
Accelerated Diffusion	$c_c = \tilde{\alpha}_C \dot{\varepsilon}^2$	Access to information (marketing)

- **Marginal Emissions** $e(t)$
- **Cumulative Emissions** $E(T) = \int_0^T e(t)dt$
- **Reference Emissions** $e_{ref} = e_0 + e_1 \cdot t$
- **Marginal Damage** $d(t) = d_1 \cdot E(t) + \frac{d_2}{2} \cdot E(t)^2$
- **Cumulative Damage (r=real discount rate)**

$$D(T) = \int_0^T e^{-r \cdot t} \cdot d(t)dt$$

- **Cost Abatement Type A** $c_A(t) = cost_A \cdot \left(e_{ref}(t) - e(t)\right)^{\gamma+1-\mathrm{b}} \approx cost_A \cdot \left(e_{ref}(t) - e(t)\right)^2$
- **Cumulative A. Cost Type A** $C_A(T) = \int_0^T e^{-r \cdot t} \cdot c_A(t)\, dt$
- **Cost Abatement Type B** $c_B(t) = cost_B \cdot (e_1 - \dot{e}(t))^{\gamma+1-b_N} \approx cost_B \cdot (e_1 - \dot{e}(t))^2$
- **Cumulative A. Cost Type B** $C_B(T) = \int_0^T e^{-r \cdot t} \cdot c_B(t)\, dt$
- **Min. Function** $\mathrm{F(T)} = D(T) + C_A(T) + C_B(T)$
- $$\int_0^T F(t)dt = \int_0^T e^{-r \cdot t} \left\{ \begin{array}{c} d_1 \cdot E(t) + \frac{d_2}{2} \cdot E(t)^2 \\ + cost_A \cdot \left(e_{ref}(t) - \dot{E}(t)\right)^2 \\ + cost_B \cdot \left(e_1 - \ddot{E}(t)\right)^2 \end{array} \right\} dt$$

Simulation Assumptions

Real discount rate 2.5%/yr.

Climate change damage $3trn/yr for an additional 500GtC emission. – global GDP mid Century typically projected in range $85-150 trn/yr

Reference emissions growth linear 800MtC/yr (2% of 2010 emissions) - corresponds closely to the reference projection of the IEA (2012).

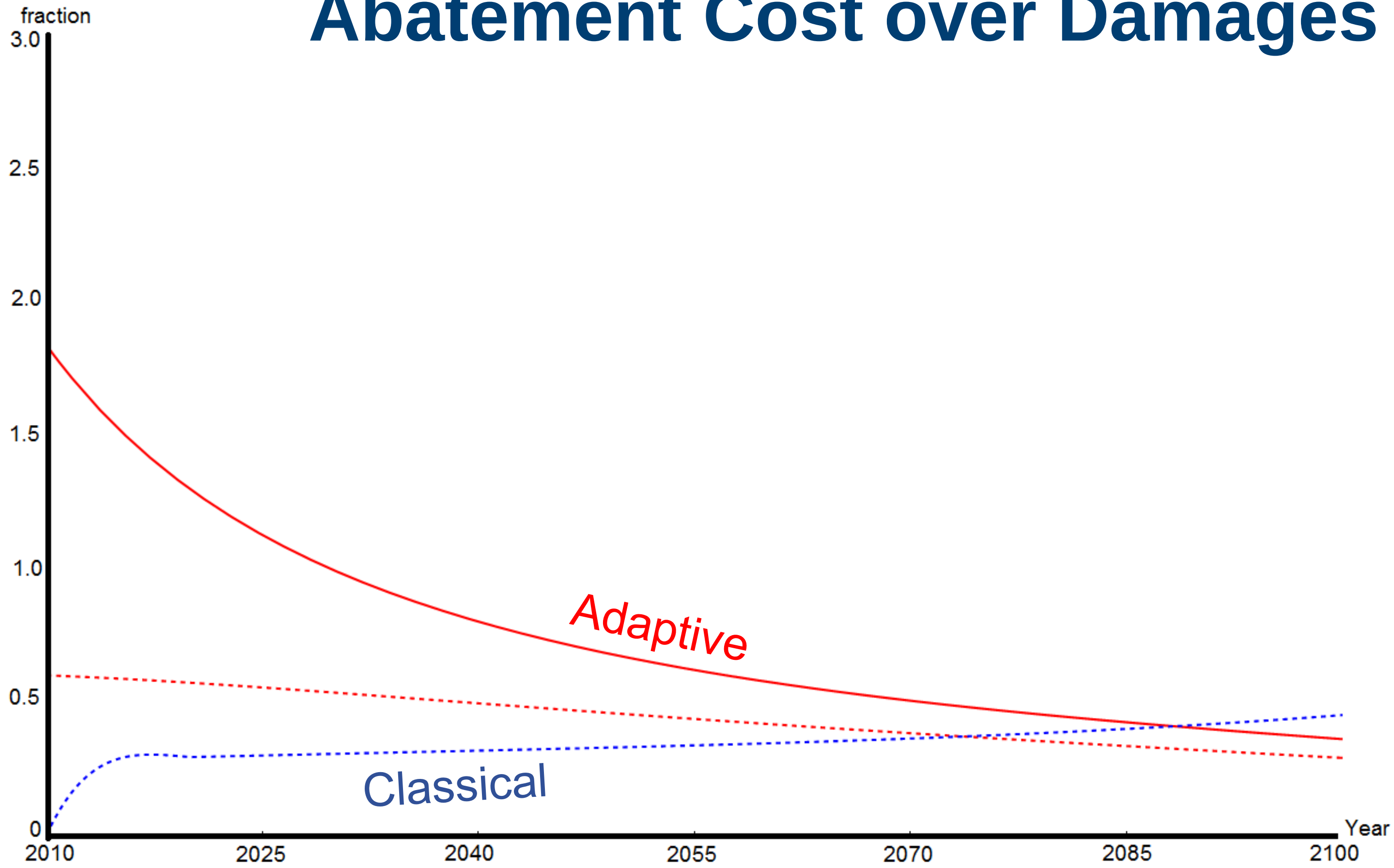
Abatement costs parameters

- Purely enduring costs (c_b =0): 50% cut in global CO_2 emissions in 2040 costs $2trn (eg 2% of GDP@$100trn). This is towards the pessimistic end of literature.

- Purely transitional costs (c_a =0): the same cutback, on a linear trajectory of abatement, results in the same total integrated cost over the 30-year period, but these are now attributed as transitional costs of reorienting the energy system over these decades.

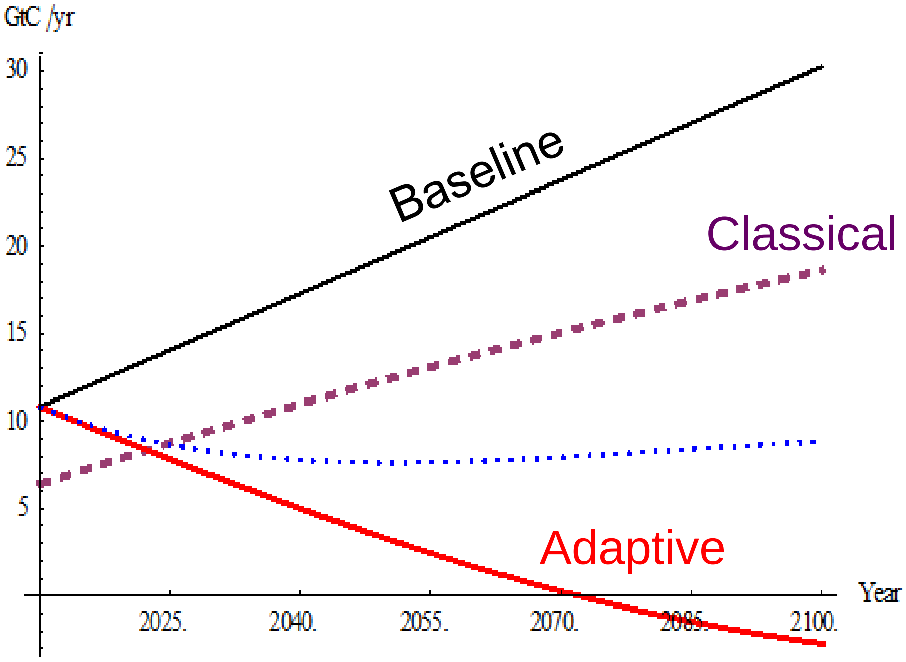
Optimal Climate Policies

Abatement Cost over Damages

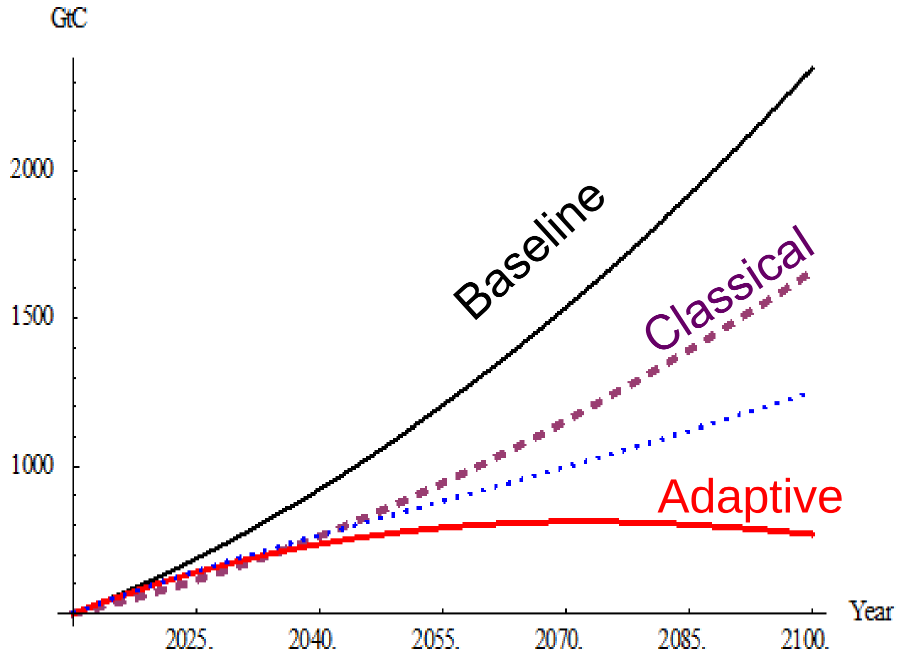


Optimal Climate Policies

Emissions

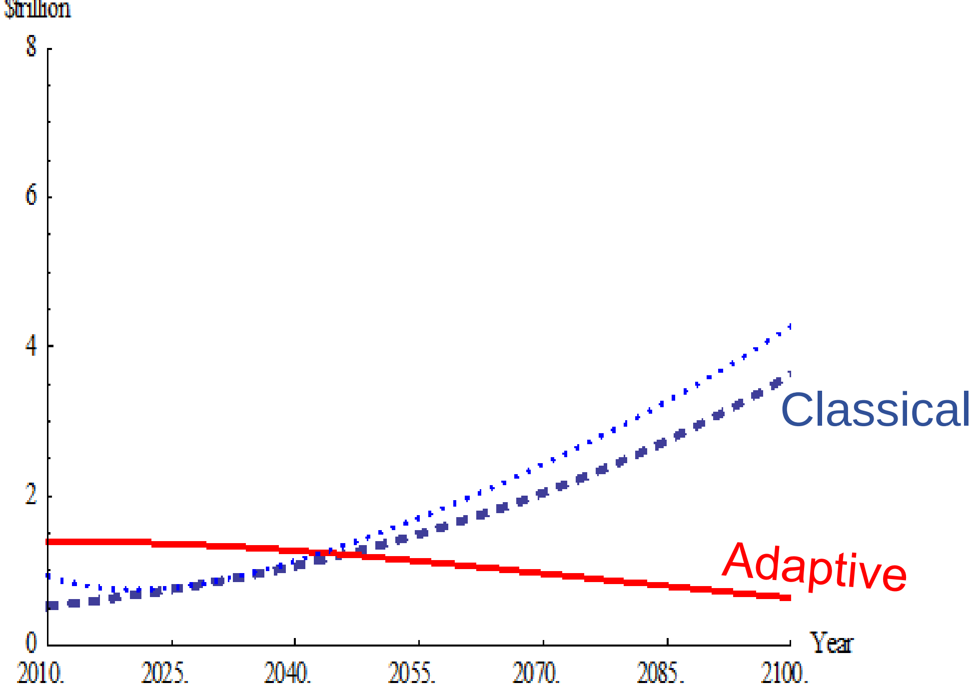


Cumulative Emissions

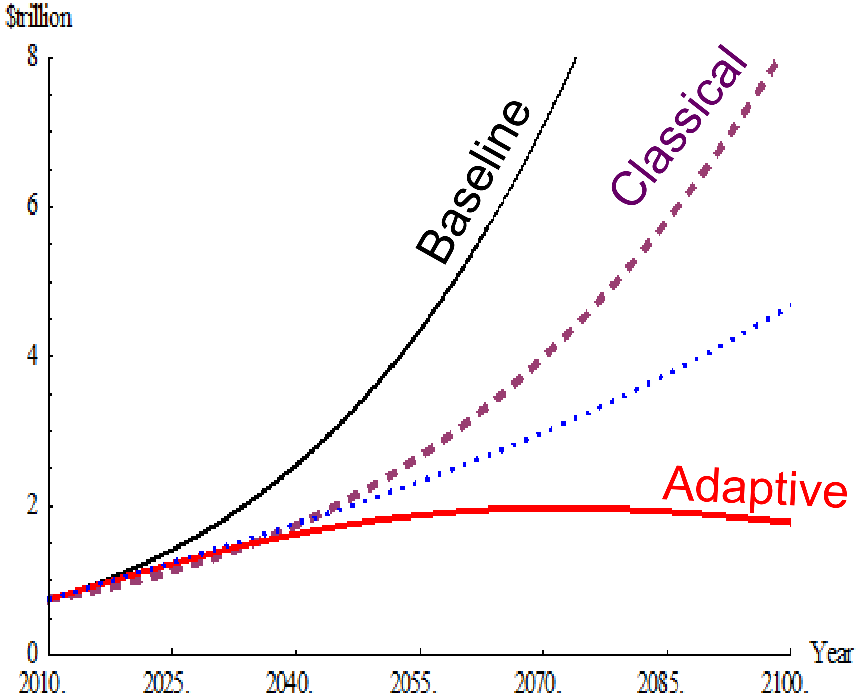


Optimal Climate Policies

Abatement Cost



Damages



Conclusions

- Low-carbon futures require the development of new long-lived install capacity and their underlying supply chain. Therefore, the **rate of change** is an important component of the abatement cost.

- Attention to **inertia** therefore results in **smoother time profiles**, but also higher investment efforts early on to build up new capabilities and change the course of the energy system, as early and smoothly as possible.

Thanks

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