46770 Integrated energy grids

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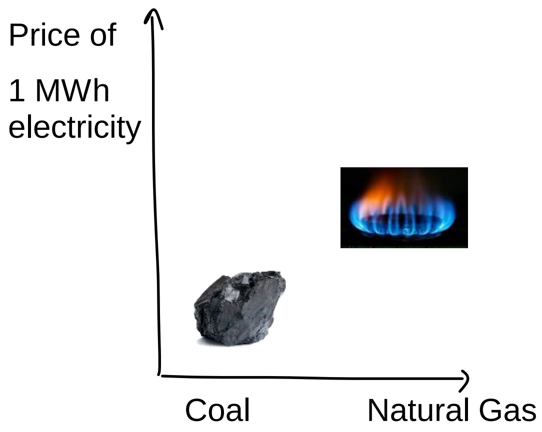
Lecture 9 – Limiting CO2 emissions

Introduction

How can we ensure that the cost optimization also leads to CO_2 emissions reductions?

+ CO_2 tax



A CO_2 tax can be imposed to alter the merit order of generators

How is that related to our optimization problem?

Learning goals for this lecture

- Demonstrate cost recovery in electricity markets
- Explain how the CO2 price affects the cost recovery in electricity markets
- Interpret the meaning of the Lagrange/KKT multiplier associated with the CO2 emissions constraints and analyze its value.
- Formulate join capacity and dispatch optimization with CO2 emissions constraints on a computer.
- Define financial discount rate and social discount rate
- Calculate the cost annualization factor
- Describe the different approach that classic economy has taken to include climate change in economic optimization

Cost recovery in electricity markets

Cost recovery in optimized markets ("non-profit rule")

Now our optimization variables are the energy $g_{s,t}$ generated by every generator s in every time step t and the installed capacity G_s of every generator

$$
\begin{cases}
\min_{g_{s,t},\, G_s} \left[\sum_s c_s G_s + \sum_{s,t} o_s \, g_{s,t} \right] \\
\text{subject to:} \\
\sum_s g_{s,t} - d_t \; = 0 \leftrightarrow \lambda_t \\
-g_{s,t} + G_s \geq 0 \quad \leftrightarrow \quad \overline{\mu_{s,t}}
\end{cases}
$$

$$
0 = \frac{\partial \mathcal{L}}{\partial g_{s,t}} = \frac{\partial f}{\partial g_{s,t}} - \sum_i \lambda_i \frac{\partial h_i}{\partial g_{s,t}} - \sum_j \mu_j \frac{\partial g_j}{\partial g_{s,t}} = o_s - \lambda_t^* + \overline{\mu_{s,t}^*} = 0 \quad \rightarrow \quad o_s = \lambda_t^* - \overline{\mu_{s,t}^*}
$$

$$
0 = \frac{\partial \mathcal{L}}{\partial G_s} = \frac{\partial f}{\partial G_s} - \sum_i \lambda_i \frac{\partial h_i}{\partial G_s} - \sum_j \mu_j \frac{\partial g_j}{\partial G_s} = c_s - \sum_t \overline{\mu_{s,t}^*} \cdot (1) = 0 \quad \rightarrow \quad c_s = \sum_t \overline{\mu_{s,t}^*}
$$

Cost recovery in optimized markets ("non-profit rule")

Total cost for generator s

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = c_s G_s^* + \sum_t (\lambda_{s,t}^* - \overline{\mu_{s,t}^*})\, g_{s,t}^*$$

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = c_s G_s^* + \sum_t \lambda_t^* g_{s,t}^* - \underbrace{\sum_t \overline{\mu_{s,t}^*}}_{c_s}\, \underbrace{g_{s,t}^*}_{G_s^*}$$

This is only true if the constraint is binding, but otherwise $\overline{\mu_{s,t}^*} = 0$

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = \cancel{c_s G_s^*}^{\,0} + \sum_t \lambda_t^* g_{s,t}^* - \cancel{c_s G_s^*}^{\,0}$$

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = \sum_t \lambda_t^* g_{s,t}^*$$

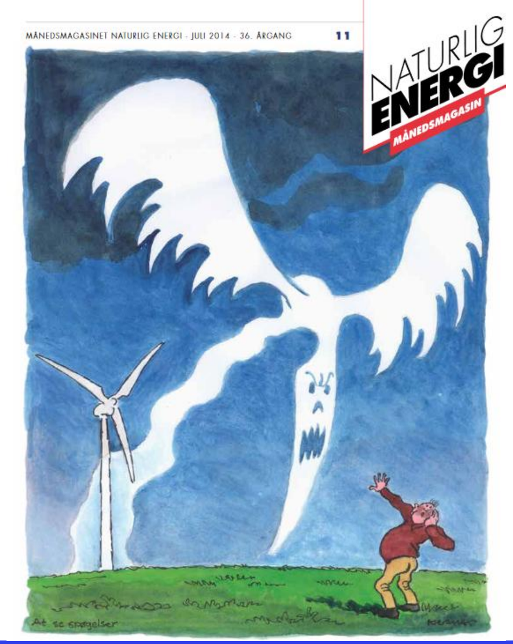
The generator costs (fixed and variable) are **exactly fully-recovered** form market revenues (generation times market price). This is known as **long-term market equilibrium** or **non-profit rule**.

If a price cap is set in the market, this is not true anymore. Some countries set a price cap and use capacity markets to compensate for the unsuccessful recovery of capital cost.

Assumptions included in the model / Limitations

The optimization problem makes three assumptions:

- Perfect competition: no generator has the power to impose artificially high electricity prices.
- Long-term market equilibrium: thanks to market revenues every technology recovers exactly its cost (fixed & variable) throughout its lifetime. This requires that, for some hours, electricity prices are higher than the marginal cost of the most expensive technology.
- Perfect foresight through the year: This might not be true (e.g., the model assumes that reservoir hydropower can be used at the optimal time).



We can include additional constraints to represent social acceptance issues (e.g., limit transmission expansion or the maximum capacity for onshore wind).

$$\sum_{l} Capacity_l \cdot Length_l < Transmission\ Cap$$

We can search for alternative solutions with higher public acceptance and quantify the economic impacts.

Global CO_2 constraint

Global CO_2 constraint

We can add a constraint to limit the total CO_2 emissions in the system

$$\sum_{s,t} \frac{\epsilon_s}{\eta_s} g_{s,t} \leq CAP_{CO2} \quad \leftrightarrow \quad \mu_{CO2}$$

where ϵ_s are the specific emissions per technology (in kgCO2/$MWh_{thermal}$), and η_s is the efficiency of the generator (in $MWh_{electricity}$ / $MWh_{thermal}$)

μ_{CO2} is the Lagrange or Karush-Kuhn-Tucker (KKT) multiplier associated with the CO_2 constraint. It represents the change in the objective function at the optimal solution, with respect to a small change in the constraint.

Small change in constraint : $CO_2\ limit^* = CO_2\ limit + 1\ \text{tonne}$

Change in objective function : $System\ cost^* = System\ cost + \Delta System\ cost$

Hence μ_{CO2} represents the cost of 1 tone of CO_2

- If $\mu_{CO2} = 0$ the constraint is not binding.
- If $\mu_{CO2} \neq 0$ we would obtain the same solution if we remove the constraint and add a CO_2 price equal to μ_{CO2}

μ_{CO2} is also known as **CO_2 price, CO_2 tax, shadow price or marginal abatement cost**

Setting a global CO_2 constraint is equivalent to adding a CO_2 tax

If we repeat the demonstration of cost recovery in optimized markets (“non-profit rule), including the CO_2 constraint

$$\left\{\begin{array}{l}
\min_{g_{s}, G_s} \left[\sum_s c_s G_s + \sum_{s,t} o_s \, g_{s,t} \right] \\
\text{subject to:} \\
\sum_s g_{s,t} - d_t = 0 \leftrightarrow \lambda_t \\
-g_s + G_s \geq 0 \quad \leftrightarrow \quad \overline{\mu_{s,t}} \\
-\sum_{s,t} \frac{\epsilon_s}{\eta_s} g_{s,t} + CAP_{CO2} \geq 0 \quad \leftrightarrow \quad \mu_{CO2}
\end{array}\right.$$

The derivative of the Lagrangian with respect to the generation gets an extra factor

$$0 = \frac{\partial \mathcal{L}}{\partial g_{s,t}} = \frac{\partial f}{\partial g_{s,t}} - \sum_i \lambda_i \frac{\partial h_i}{\partial g_{s,t}} - \sum_j \mu_j \frac{\partial g_j}{\partial g_{s,t}} = o_s - \lambda_t^* + \overline{\mu_{s,t}^*} + \mu_{CO2} \frac{\epsilon_s}{\eta_s} = 0 \quad \rightarrow \quad o_s = \lambda_t^* - \overline{\mu_{s,t}^*} - \mu_{CO2} \frac{\epsilon_s}{\eta_s}$$

Setting a global CO_2 constraint is equivalent to adding a CO_2 tax

We repeat the demonstration of cost recovery in optimized markets (“non-profit rule)

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = c_s G_s^* + \sum_t (\lambda_{s,t}^* - \overline{\mu_{s,t}^*} - \mu_{CO2} \frac{\epsilon_s}{\eta_s})\, g_{s,t}^*$$

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = c_s G_s^* + \sum_t (\lambda_t^* - \mu_{CO2} \frac{\epsilon_s}{\eta_s}) g_{s,t}^* \;\; - \underbrace{\sum_t \overline{\mu_{s,t}^*}}_{c_s}\, \underbrace{g_{s,t}^*}_{G_s^*}$$

This is only true if the constraint is binding, but otherwise $\overline{\mu_{s,t}^*} = 0$

$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = \cancelto{0}{c_s G_s^*} + \sum_t (\lambda_t^* - \mu_{CO2} \frac{\epsilon_s}{\eta_s}) g_{s,t}^* \;\; - \cancelto{0}{c_s G_s^*}$$

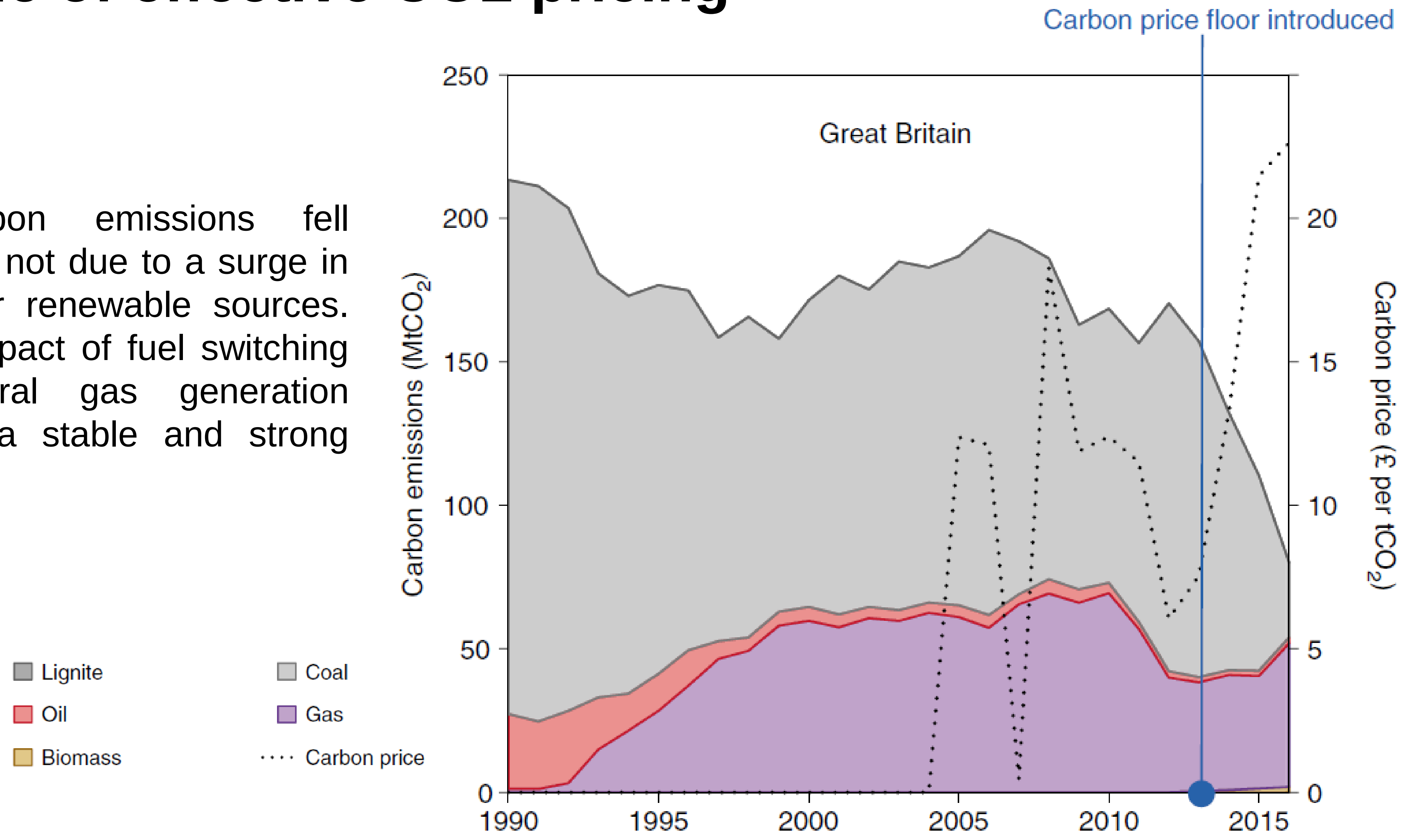
$$c_s G_s^* + \sum_t o_s\, g_{s,t}^* = \sum_t \underbrace{(\lambda_t^* - \mu_{CO2} \frac{\epsilon_s}{\eta_s})}\, g_{s,t}^*$$

Market revenues minus cost of
CO_2 price times generation

This shows that **setting a global CO_2 constraint is equivalent to adding a CO_2 price**
(i.e. substituting o_s by $o_s + \mu_{CO2} \frac{\epsilon_s}{\eta_s}$)

An example of effective CO2 pricing

"Great Britain carbon emissions fell drastically and quickly not due to a surge in low-carbon nuclear or renewable sources. Instead, it was the impact of fuel switching from coal to natural gas generation incentivized through a stable and strong carbon price. "



Source: Wilson and Staffell, Rapid fuel switching from coal to natural gas through effective carbon pricing, Nature (2018)

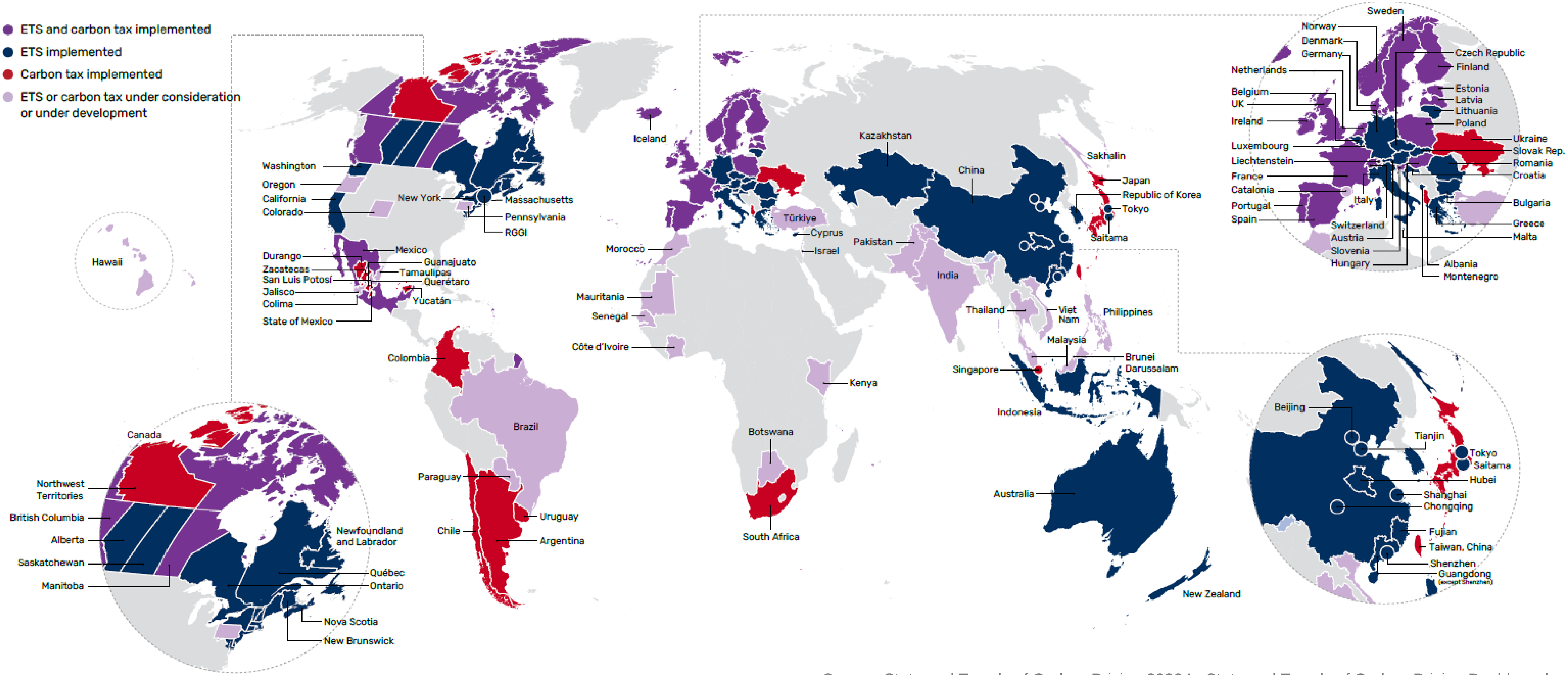
Current CO_2 price in Europe

In Europe, electricity generators need to buy their rights to emit CO_2 in the Emissions Trading System (ETS).

Currently ETS includes power and heat generation, energy-intensive industry sectors, commercial aviation.

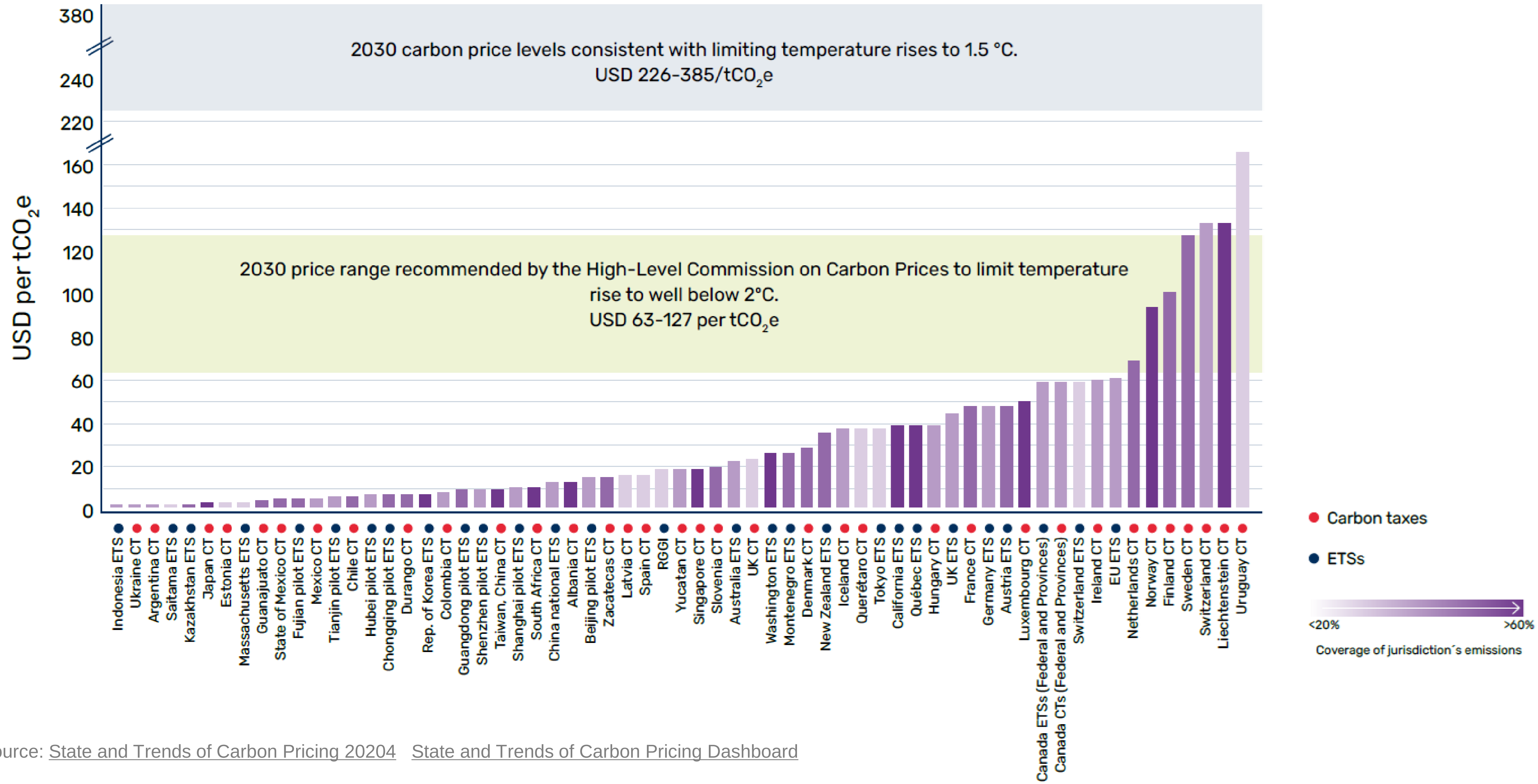
EU carbon price tracker

Existing CO_2 tax in different countries



Source: State and Trends of Carbon Pricing 20204 State and Trends of Carbon Pricing Dashboard

CO_2 price levels continue to fall short of the ambition needed to achieve the Paris Agreement goals



Source: State and Trends of Carbon Pricing 20204 State and Trends of Carbon Pricing Dashboard

Cost annualization and financial discount rate

Cost annualization and financial discount rate

The investment cost I_0 needs to be recovered by payments in every year, which can be expressed by the *Eq. A*.

$$I_0 = \frac{I_A}{(1+r)^1} + \frac{I_A}{(1+r)^2} + \frac{I_A}{(1+r)^3} + \cdots + \frac{I_A}{(1+r)^N} \qquad (Eq.\ A)$$

If we multiply *Eq. A* by $\frac{1}{1+r}$, compare it to *Eq.A* and subtract both expressions

$$I_0 = \frac{I_A}{(1+r)^1} + \frac{I_A}{(1+r)^2} + \frac{I_A}{(1+r)^3} + \cdots + \frac{I_A}{(1+r)^N}$$

minus

$$\frac{I_0}{1+r} = \frac{I_A}{(1+r)^2} + \frac{I_A}{(1+r)^3} + \frac{I_A}{(1+r)^4} + \cdots + \frac{I_A}{(1+r)^{N+1}}$$

We get *Eq. B*.

$$I_0\left(1 - \frac{1}{1+r}\right) = \frac{I_A}{(1+r)^1} - \frac{I_A}{(1+r)^{N+1}} \qquad (Eq.\ B)$$

Cost annualization and financial discount rate

We now multiply Eq. B by $(1+r)^{N+1}$ and get:

$$I_0\left((1+r)^{N+1} - (1+r)^N\right) = I_A\left((1+r)^N - 1\right)$$

Finally, by reordering the equation we get:

$$\boxed{I_A = I_0 \frac{(1+r)^N \cdot r}{(1+r)^N - 1}}$$

Cost annualization

r = financial discount rate

N = number of years the asset is in operation

I_A = annualized cost

I_0= capital cost, investment on the first year.

For investment in the energy sector, a financial discount rate of 7% is typically assumed.

Including climate change in economic optimization and social discount rate

Including climate change in economic optimization

Initially, **cost-benefit analyses** were developed, aiming at evaluating to what extent the cost of climate change mitigation compensates for the avoided climate change impacts.

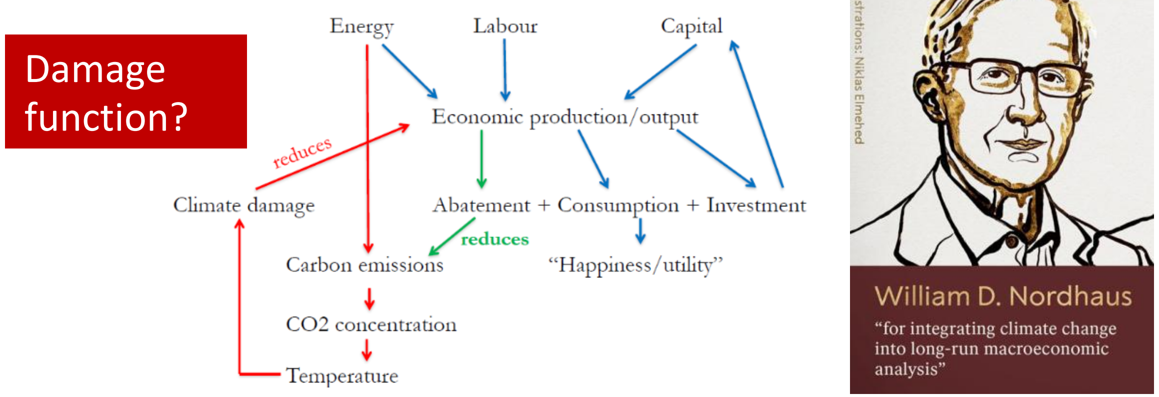
Which temperature increase is cost-optimal (from an economic point of view)?

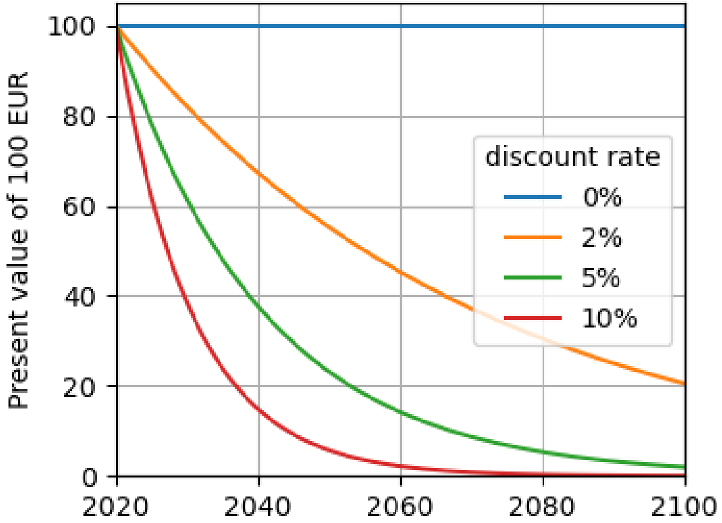
The main challenges were:

1. How to quantify impacts of climate change through damage functions or using the social cost of carbon (SCC)

2. The assumed social discount rate determines the results

Figure 1: Schematic illustration of the DICE model





Stern/Nordhaus controversy:

- Nordhaus found optimal temperature increase 3.5ºC (r =4.5%), SSC of 10 USD/tCO2 (r =3%)
- Stern: SSC of 85 USD/tCO2 (r =1.4%)

D. Roberts, Discount rates: A boring thing you should know about , 2012

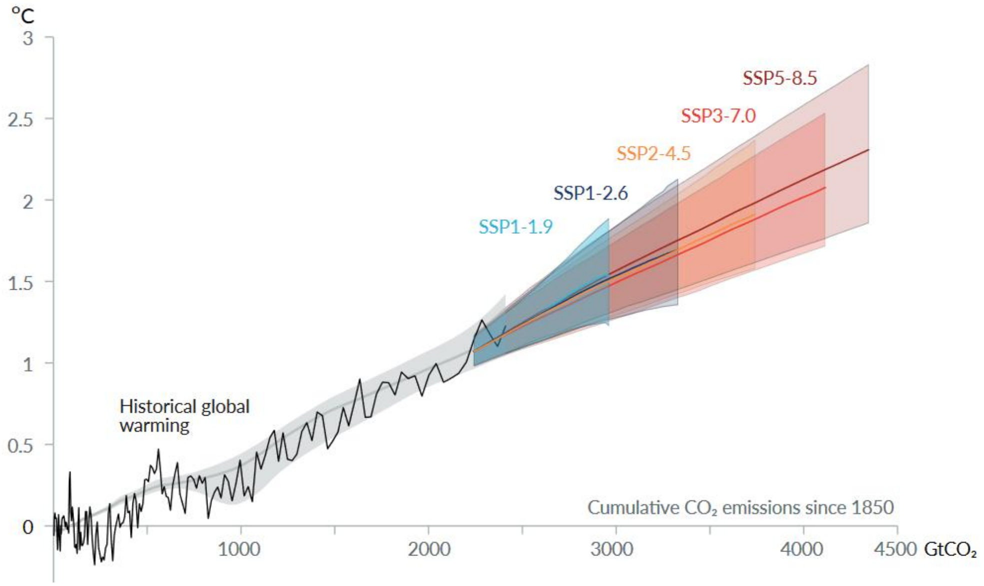
Including climate change in economic optimization

Later, **cost-effectiveness analyses** were developed, aim at estimating the most cost-effective strategy to attain a climate target.

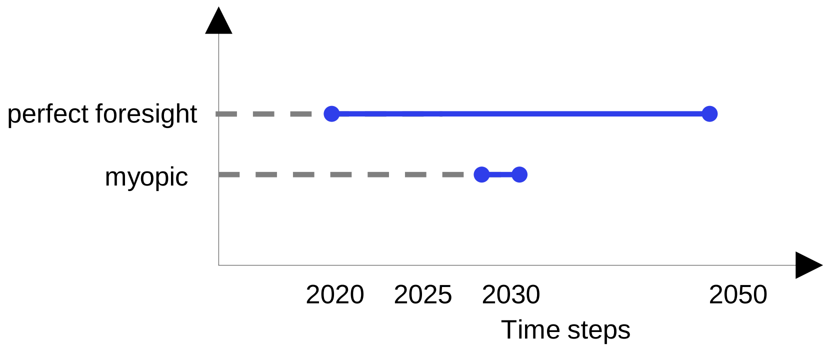
What is the best way of transforming the system while keeping emissions below CO_2 budget?

We can impose the CO_2 constraint throughout a transition path to limit cumulative emissions

$$\cancel{\sum_{s,t} CO_2\ emissions \leq CO_2\ limit \quad \leftrightarrow \quad \mu_{CO2}} \qquad\qquad \int_{2020}^{2050} \sum_{s,t} CO_2\ emissions \leq CO_2\ budget$$



We can assume perfect-foresight or myopic transition.



The perfect-foresight approach obtains the optimal transformation path and is influenced by the assumed social discount rate. The myopic approach captures the short-sighted behaviour of policy-makers and the sunk costs of bad decisions.

Problems for this lecture

Problems 9.1, 9.2 (**Group 18**)

Problems 9.2 (**Group 19**)