Energy System Modelling
Summer Semester 2019, Lecture on Multi-Horizon Dynamic Investment

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27th June 2019

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Review

Short-run efficiency

Short-run efficiency is concerned with the **efficient operation** of the existing energy system, assuming that the capacities of all investments are fixed.

Example: Power plant dispatch for inelastic demand d. All capacities G_s [MW] are fixed. We optimise the **dispatch** g_s [MW], assuming that the **marginal costs** o_s [€/MWh] scale linearly with the dispatch. We minimise **total operational costs**:

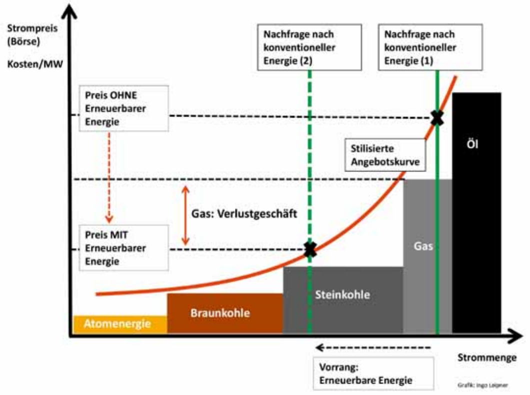
$$\min_{\{g_s\}} \sum_s o_s g_s$$

with constraints

$$\sum_s g_s = d \qquad \leftrightarrow \qquad \lambda$$

$$g_s \leq G_s \qquad \leftrightarrow \qquad \bar{\mu}_s$$

$$-g_s \leq 0 \qquad \leftrightarrow \qquad \underline{\mu}_s$$



Long-run efficiency

Long-run efficiency is concerned with the **efficient operation** and **the efficient dimensioning of investments** in the energy system.

Example: Power plant **dispatch** $g_{s,t}$ (costs o_s) and **capacities** G_s (annualised costs c_s) are optimised over a year of hourly time periods t with demand d_t:

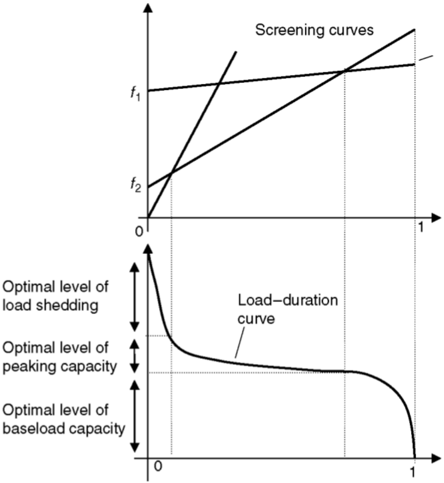
$$\min_{\{g_{s,t}, G_s\}} \sum_{s,t} o_s g_{s,t} + \sum_s c_s G_s$$

with constraints

$$\sum_s g_{s,t} = d_t \qquad \leftrightarrow \qquad \lambda_t$$

$$g_{s,t} \leq G_s \qquad \leftrightarrow \qquad \bar{\mu}_{s,t}$$

$$-g_{s,t} \leq 0 \qquad \leftrightarrow \qquad \underline{\mu}_{s,t}$$



Multi-horizon investment: Motivation

Multi-horizon investment

Dynamic multi-horizon investment is concerned with the **changing capacities of investments** in the energy system over many years or even **decades**.

At which point in time should we invest in renewables/gas/storage?

We consider several time horizons, typically years, in which plants can be dismantled or built.

Why are we concerned with changes over decades?

Multi-horizon investment

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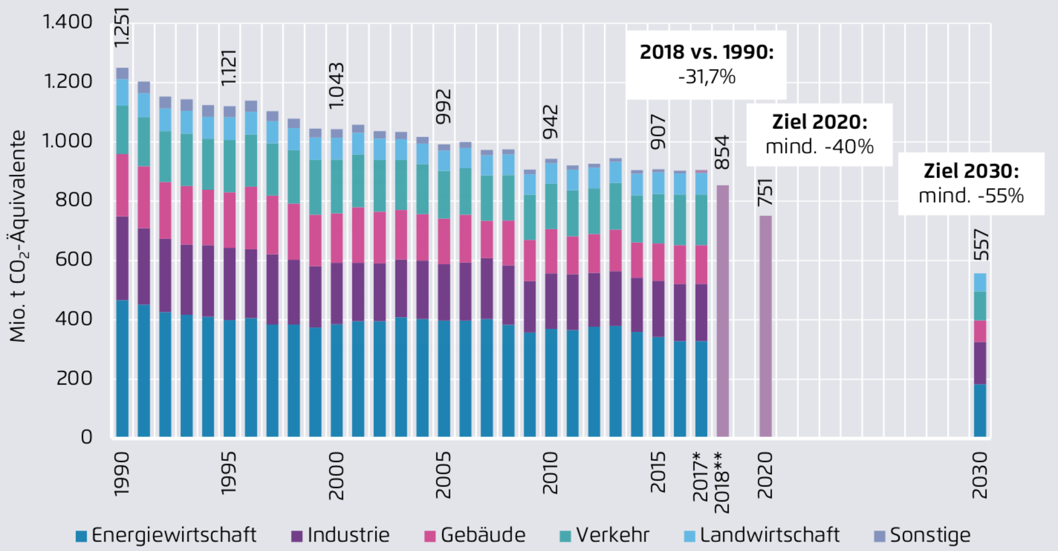
Why are we concerned with changes over decades?

Since many aspects of the energy system change over decades, e.g.:

- **Energy consumption** (particularly in developing countries)
- **Resource scarcity** (scarcity of oil, cobalt, rare earth metals, etc.)
- **Political targets** (e.g. reduction of greenhouse gas emissions)
- **Maturity, costs and other parameters** (e.g.. efficiency) of technologies
- **Economic growth**
- **Bahavioural change** (car sharing, online gaming, etc.)

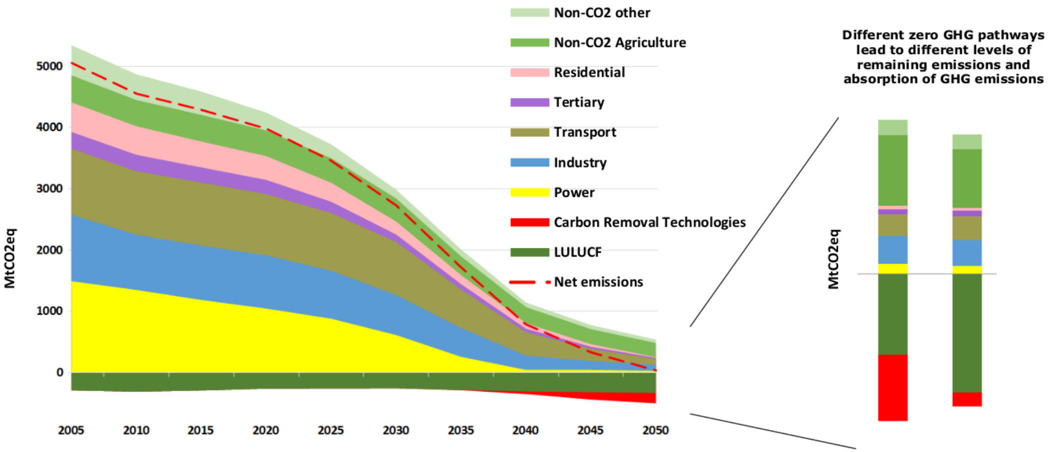
Example: political targets



Source: Agora Energiewende

Example: Net-Zero Emissions by 2050

Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**

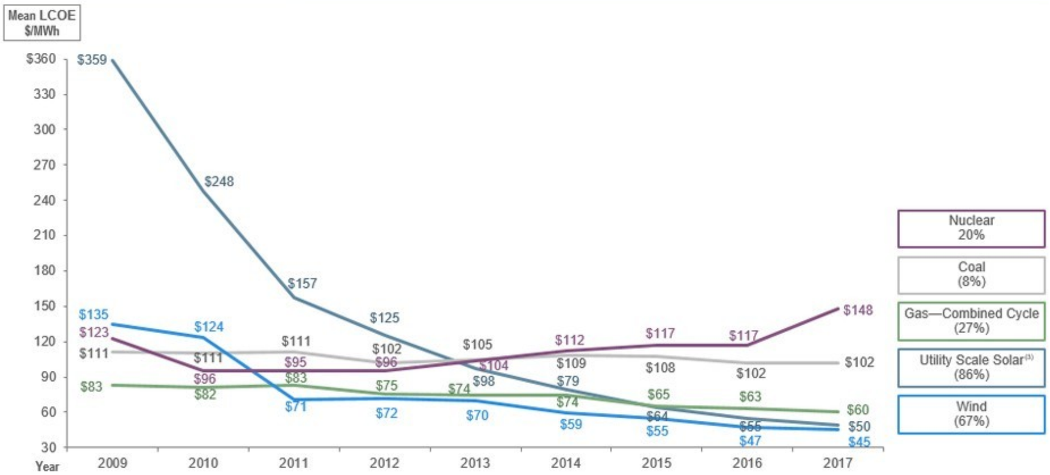


Source: European Commission 'Clean Planet for All', 2018

Example: Cost Developments of Renewable Energy

LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output

Selected Historical Mean LCOE Values[2]



Source: Lazard's LCOE Analysis V11

Multi-horizon investment: Theoretical formulation

Discounted Total Costs

We will consider the total costs over **multiple years** $a = 1, \ldots A$.

How do we compare costs in 2020 to those in 2040?

Discounted Total Costs

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How do we compare costs in 2020 to those in 2040?

The totals costs are expressed in their **present value** using the **discount rate** r (see lecture 8), to allow comparison between different years.

For costs (or income) in year a we **discount** the costs with a factor

$$\frac{1}{(1+r)^a}$$

because we could have invested until this year a with return r.

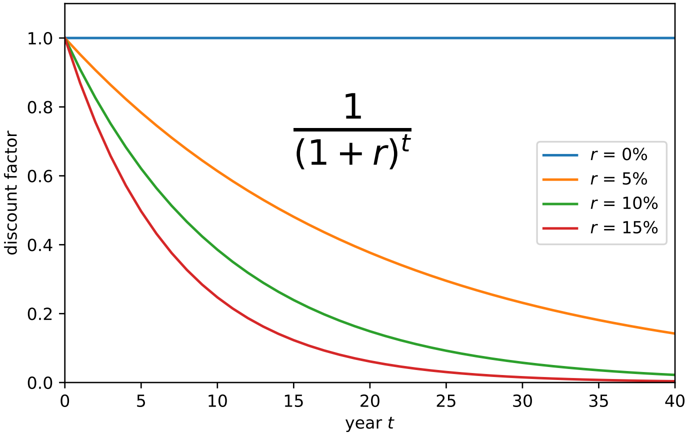
Costs in the future are **worth less** from today's point of view.

For rate r we optimised the **discounted total costs**

$$\sum_{a=1}^{A} \frac{1}{(1+r)^a} \{\text{Total costs in year } a\}$$

Warning: Discounting over long time periods

Over long time periods the discounting can have a very large effect....



- Long-term benefits aren't seen, e.g. long production life of nuclear power plants or benefits of long-lived efficiency measures
- Long-term costs are also suppressed, e.g. decommissioning, waste disposal, climate damages
- This is a **controversial topic!**

Example of Electricity System until 2050

We optimise the discounted total costs over 30 years from 2021 to 2050

$$\min_{\{g_{s,t,a},Q_{s,a},G_{s,a}\}} \sum_{a=1}^{A} \frac{1}{(1+r)^a} \left\{ \sum_{s,t} o_{s,a} g_{s,t,a} + \sum_{s,b} c_{s,b} Q_{s,b} \mathbb{I}(a \geq b) \mathbb{I}(a < b + L_s) \right\}$$

Here $Q_{s,a}$ is the new capacity built in year a, $G_{s,a}$ is the total capacity available in year a, L_s is the lifetime and $\mathbb{I}$ is an indicator function that is 1 if the condition is fulfilled, 0 otherwise. $Q_{s,a}$ may also have fixed values for $a < 1$ to represent existing capacity. $Q_{s,a}$ and $G_{s,a}$ are related by

$$G_{s,a} = \sum_{b=1}^{L_s} Q_{s,a-b}$$

The old constraints apply for each year a

$$\sum_s g_{s,t,a} = d_{s,a} \qquad \leftrightarrow \qquad \lambda_{t,a}$$

$$g_{s,t,a} \leq G_{s,a} \qquad \leftrightarrow \qquad \bar{\mu}_{s,t,a}$$

$$-g_{s,t,a} \leq 0 \qquad \leftrightarrow \qquad \underline{\mu}_{s,t,a}$$

Global constraints

With a long-term perspective we can now set exciting constraints.

For example, we can restrict total **emissions** over the period:

$$\sum_{s,t,a} e_i g_{s,t,a} \leq \mathrm{CAP}_{\mathrm{CO}_2}$$

where e_s is the specific emissions of technology s (tonnes of CO_2 per $\mathrm{MWh}_{\mathrm{el}}$).

Or limit **resource consumption** for a technology s:

$$\sum_{t,a} g_{s,t,a} \leq \mathrm{CAP}_s$$

Learning effects

Technology costs sink with accumulated manufacturing experience, particularly for new immature technologies.

We promote $c_{s,a}$ to an optimisation variable that depends on the cumulative generator capacity.

A simple **one-factor learning model** for the costs is

$$c_{s,a} = c_{s,0} \left(\sum_{b=1}^{a} Q_{s,b} \right)^{-\gamma_s}$$

where $c_{s,0}$ is the initial cost, $Q_{s,b}$ is the capacity produced in year b and γ_s is the **learning parameter**.

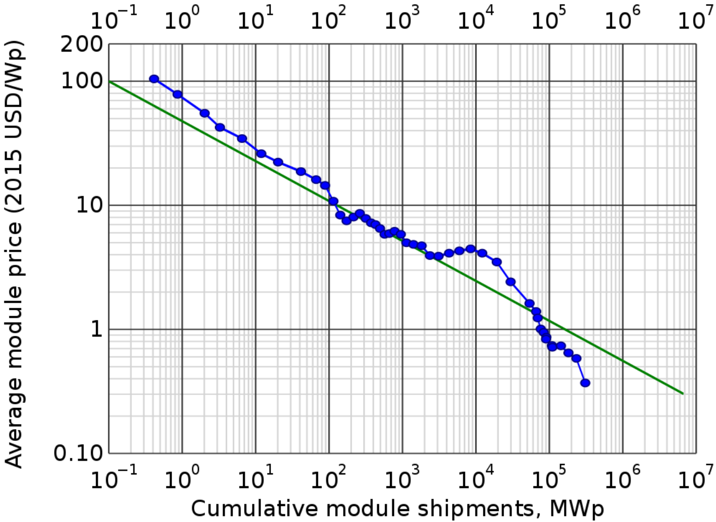
The **learning rate** LR is the reduction in cost for every doubling of production

$$LR_s = 1 - 2^{-\gamma_s}$$

Example for photovoltaics: $\gamma = 0.33 \implies$ if cumulative production doubles, the costs reduce by 20% (**Swanson's Law**).

Swanson's Law for photovoltaic modules

The underlying dynamic is a fast decay in costs with deployment (**learning-by-doing**).



More complicated learning models

In the literature there are more sophisticated learning models than the one-factor model, e.g.

- **Multi-component learning models**: different parts of the cost experience different learning rates, e.g. some parts of the cost do not experience learning, such as fixed material and labour costs, call it $c_{s,\mathrm{base}}$. Only the remainder experiences learning:

$$c_{s,a} = c_{s,\mathrm{base}} + (c_{s,0} - c_{s,\mathrm{base}}) \left(\sum_{b=1}^{a} Q_{s,b} \right)^{-\gamma_s}$$

  In the case of PV, $c_{s,\mathrm{base}}$ would include e.g. the labour costs of installation.

- **Multi-factor learning models**: the cost depends not just on the cumulative capacity, but on other factors such as knowledge stock KS through research and development

$$c_{s,a} = c_{s,0} \left(\sum_{b=1}^{a} Q_{s,b} \right)^{-\gamma_{s,1}} \left(\sum_{b=1}^{a} KS_{s,b} \right)^{-\gamma_{s,2}}$$

Multi-horizon investment: Simplified example

Simplified example

https://nworbmot.org/courses/esm-2019/lectures/notebooks/dynamic_investment.ipynb

Time period: 2021 until 2070. Discount rate: $r = 0.05$.

Constant electricity demand $d_{t,a} = d = 100$ GW.

At the start of the simulation there is already 100 GW of 20-year-old coal plants.

3 generation technologies are available that are dispatchable (for Concentrating Solar Power (CSP) need good direct solar insolation, e.g. New Mexico or Morocco).

Tech	Capital costs (€MW^{-1} a^{-1})	Marg. costs (€$\mathrm{MWh}_{\mathrm{el}}^{-1}$)	LCOE (€$\mathrm{MWh}_{\mathrm{el}}^{-1}$)	Cap factor	Emissions ($\mathrm{tCO_2 MWh}_{\mathrm{el}}^{-1}$)	Lifetime years
Coal	30*8760	20	50	1	1	40
Nuclear	65*8760	10	75	1	0	40
CSP	150*8760	0	150	1	0	30

Simplified example

Since each technology can generate continuously and the demand is constant, we assume $g_{s,t,a}$ is constant for all t

$$g_{s,t,a} = g_{s,a} \leq G_{s,a}$$

This simplifies the optimisation problem considerably:

$$\min_{\{g_{s,t,a}, Q_{s,a}, G_{s,a}\}} \sum_{a=1}^{A} \frac{1}{(1+r)^a} \left\{ \sum_s o_{s,a} g_{s,a} \cdot 8760 + \sum_{s,b} c_{s,b} Q_{s,b} \mathbb{I}(a \geq b) \mathbb{I}(a < b + L_s) \right\}$$

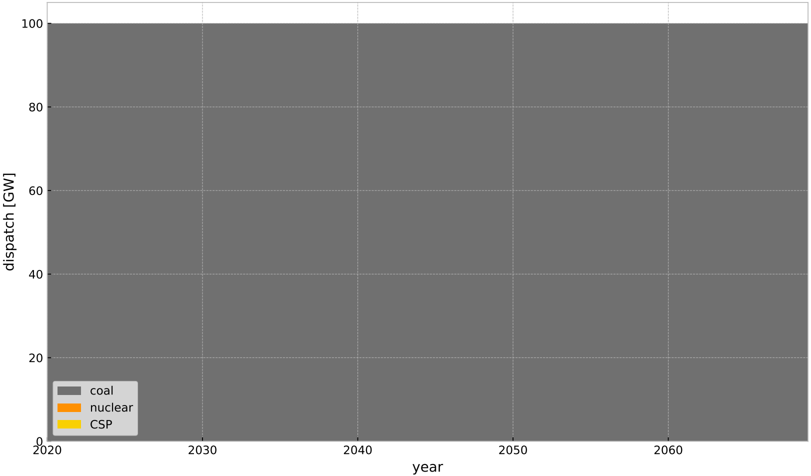
with constraints for each year a

$$\sum_s g_{s,a} = d$$

Vanilla Version: No CO_2 budget, no learning, no discounting

Only new coal is built, since it's cheapest.

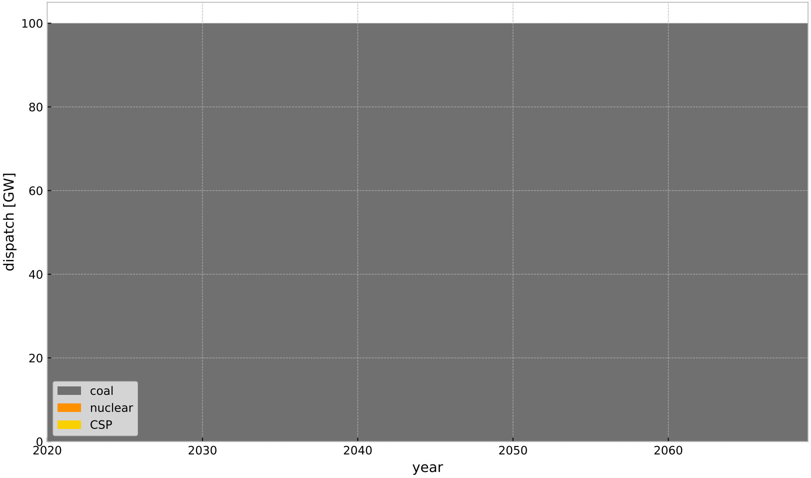
Total costs without discounting: $50€/\mathrm{MWh} \cdot 8760 \cdot 100\ \mathrm{GW} \cdot 50\ \mathrm{years} = 2190$ billion €



Vanilla Version: No CO_2 budget, no learning, discounting

Only coal is built, since it's cheapest.

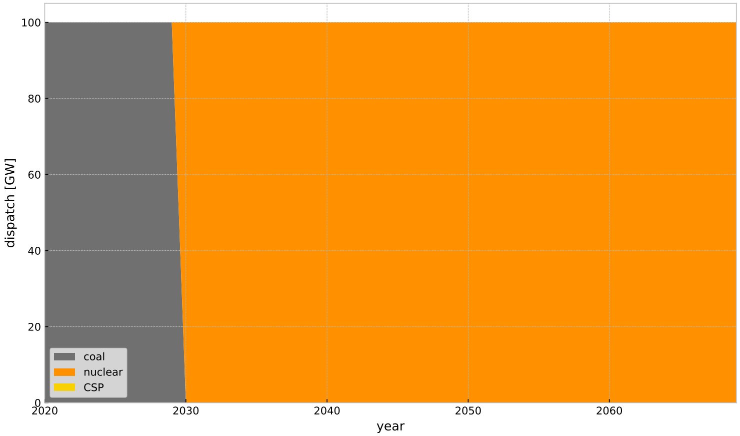
Total costs with discount rate 5%: 840 billion €



CO_2 budget, no learning, discounting

Limit CO_2 to 20% of coal emissions. Nuclear takes over before coal lifetimes are finished. Why is it built only later in the period (even when no existing plants assumed)? (Hint: discounting)

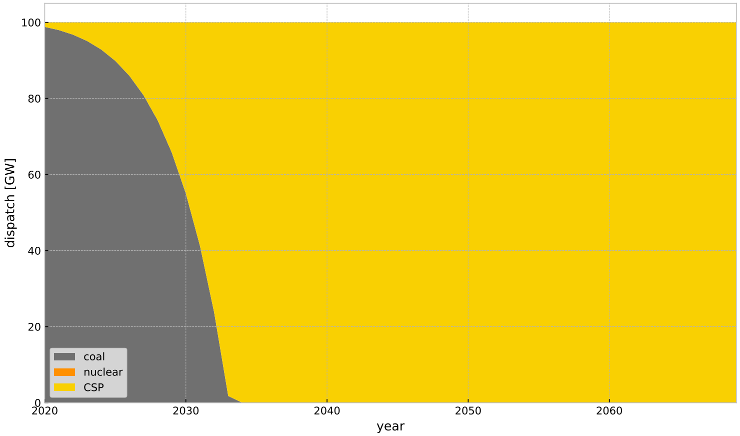
Total costs with discount rate 5%: 1147 billion €



CO_2 budget, learning for CSP, discounting

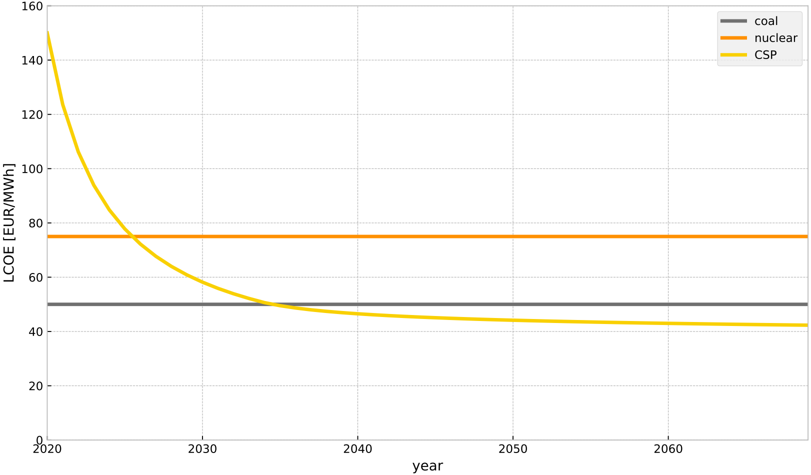
Limit CO_2 to 20% of coal emissions. CSP has learning rate 20%, $\gamma = 0.33$, and a base long-term potential LCOE of 35 €/MWh that represents material and labour costs.

Total costs with discount rate 5%: 1020 billion €



CO_2 budget, learning for CSP, discounting

LCOE needs subsidy initially to push down learning curve, since it is more expensive than incumbent technologies. But from 2034 onwards it is the most competitive technology.



Lessons from this example

- Non-linear effects such as learning-by-doing make the results hard to predict
- It may be cost-effective in the long-run to subsidise technologies that are uncompetitive today
- Depending on how subsidy and policy is arranged, there could be **path dependencies**

To improve the realism of this example we need to:

- Include more technologies, spatial resolution
- Consider more representative times per year to capture the variability of renewables and load

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