Lecture 6: Environmental policies: trade, firms, and technologies

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Objective of the lecture

The **objective of the previous lectures** was to provide a comprehensive framework to think about environmental problems:

- where does the problem come from (environmental problem);
- why does the market fail at solving the problem by itself (extenality, other market failures);
- to what extent this problem affects social welfare, and how much efforts should we perform to address it (the target);
- what is the best way to address it given the impact of policies on social welfare (equity and efficiency of instruments);
- what are the political limitations that may undermine the implementation of these policies (lack of governance, free-riding, and incorrect beliefs).

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The **objective of this last lecture** is no more to build a framework, but rather to cover specific topics (trade/globalization and the environment, the EU-ETS, and the future of climate-related technologies) with a focus on factual knowledge necessary to think about policies.

Road map

1. Trading pollution permits: the EU-ETS
2. Environmental policies in the long-run: technologies
3. The climate technology revolution
4. Conclusion

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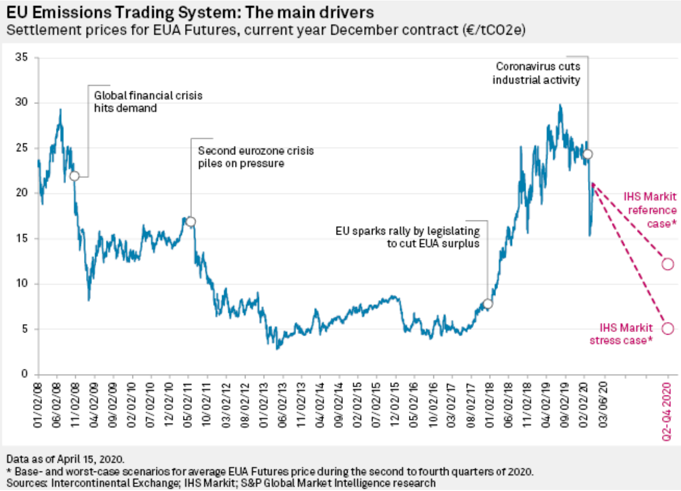
EU-ETS: how it works

Although carbon taxes are difficult to implement for political reasons, large carbon pricing schemes have been implemented with success in several places (e.g. China, Canada, New Zealand, Japan, certain U.S. States, etc.) through emission trading schemes.

As of today, the European one ("EU-ETS") launched in 2005 is the largest:

- the EU-ETS applies to about 11,000 installations (power plants and industrial plants) and airline companies, covering around 40% of the EU's greenhouse gas emissions;
- it sets a cap on the total amount of CO_2, N_2O, and PFCs (perfluocarbons) that can be emitted by these installations;
- this cap declines over time (by 1.74% per year between 2013 and 2020, 2.2% from 2021) in order to achieve Europe's emissions targets;
- companies either receive or buy emission allowances within this cap, and can also buy international credits from elswhere in the world;
- at the end of each year, companies must surrender allowances that cover their emissions. Their excess can be kept for the next year or sold to other companies.

The evolution of permit prices



→ Historically, permit prices have been very low: too many permits allocated relative to firms' capacity to reduce their emissions (especially in a post 2008-crisis context).

Estimated effect on emissions

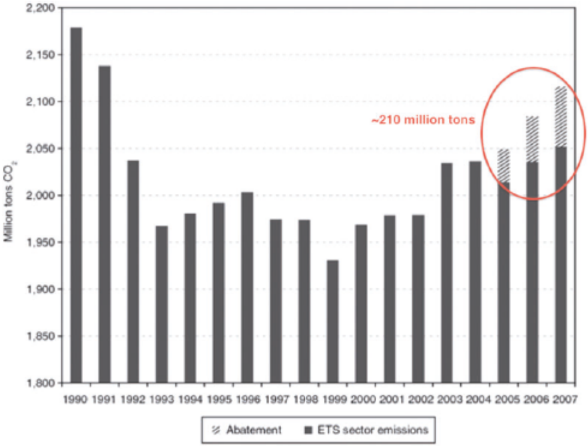
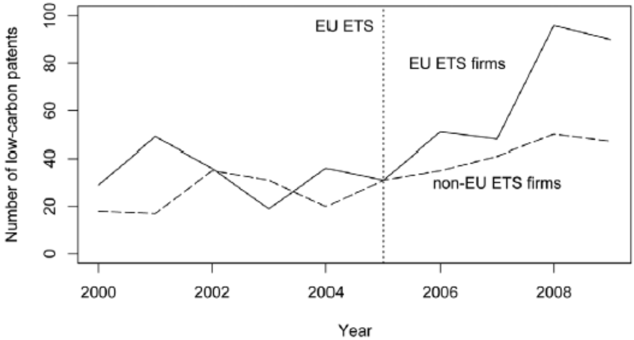


Figure 2 Emissions and abatement in the EU
Source: Ellerman, Convery, and de Perthuis (2010). Figure 6.2, p. 165 based on CITL, World Economic Outlook database, and EEA greenhouse gas data.

During the first phase (from 2005 to 2007), estimated abatement of emissions in regulated firms around 3% (see Ellerman, Convery, and de Perthuis, 2010).

Estimated effect on low-carbon innovation

FIGURE 5.—LOW-CARBON PATENTS BY MATCHED EU ETS AND NON–EU ETS FIRMS



Using a difference-in-difference method, Calel and Dechezleprêtre (2016) show that the EU-ETS has increased low-carbon innovation (as measured by the number of patents issued) by 10%, but did not have any effect on non-regulated firms, nor on the number of innovations for other technologies.

EU-ETS: prices and effectiveness

Historically, the EU-ETS prices have been low. Two interpretations:

- the optimistic view: firms have managed to reduce their emissions to reach the target more easily than expected;
- the critical view: too much permits were initially allocated, much more abatements could have been performed if the target had been more ambitious.

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- the optimistic view: firms have managed to reduce their emissions to reach the target more easily than expected;
- the critical view: too much permits were initially allocated, much more abatements could have been performed if the target had been more ambitious.

Both views are not inconsistent with each other: low prices are both the consequence of insufficiently stringent targets given the economic context and relatively low abatement costs of many installations.

$\rightarrow$ Missed opportunity, but encouraging prospects.

EU-ETS: price and expectations

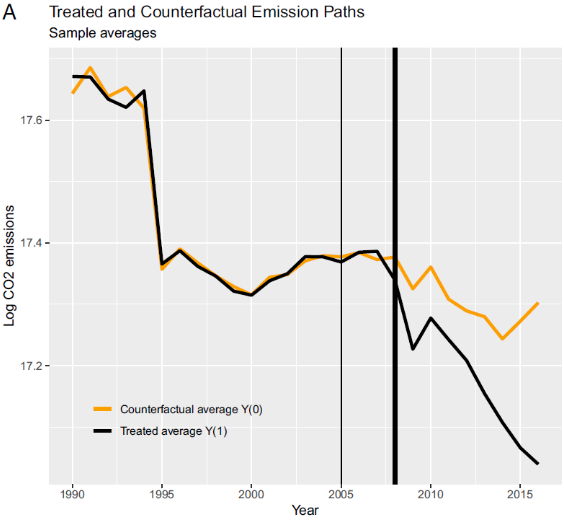
Bayer & Atkin (2020):

- low prices may not provide strong incentives to reduce pollution, but they may also reflect firms' expectations about higher future prices, leading to anticipated reductions in emissions.

  $\rightarrow$ Even if it operates at a low price, the existence of the carbon market creates a credible threat of future heavier regulation;

- using a generalized synthetic control method, they estimate that between 2008 and 2016 the ETS has decreased emissions by 3.8% relative to total CO_2 emissions in the EU.

Estimated effect on emissions



EU-ETS: prospects for the future

In 2021, the ETS has entered in its fourth phase, with a more rapid decrease of the emission cap. To address the problem of low but highly volatile prices, the European Comission had aldready taken additional measures:

- the auctioning of additional permits has been postponed (although not cancelled);
- a Market Stability Reserve (MSR) has been implemented to adjust the number permits in circulation, just like a central bank targets inflation through money supply.

Future plans regarding the extension of the EU-ETS (stringency, number of sectors covered) will be part of the European Green Deal.

The recent trend of the ETS price

Source: https://tradingeconomics.com/commodity/carbon

Carbon market linking

Another potential prospect for the evolution of the ETS is its merger with other carbon markets.

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On the one hand, this could:

- build up climate cooperation across countries;
- limit competitiveness issues between them;
- harmonize mitigation efforts;
- increase the market's liquidity;
- pool the risks associated with demand uncertainty (see Doda et al, 2019);
- etc.

On the other hand, it could:

- reduce countries' control over their environmental objective;
- dampen more ambitious initiatives;
- result in an unequal distribution of gains;
- etc.

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Assessing the costs of pollution abatements

Certain actions to reduce pollution cost more than others. The idea of market-based instrument is to set a price on pollution, say x€/tCO_2, such that all actions that cost less than that price are undertaken.

This approach requires little information about the costs associated with specific actions: market forces naturally select the least costly ones.

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However, in practice:

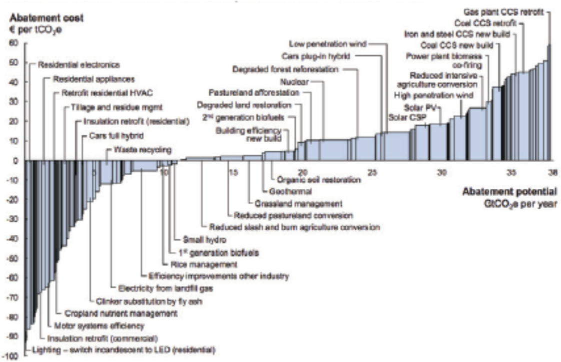
- policy makers are often reluctant to implement market-based instruments in general, and carbon pricing in particular;
- the existence of other market failures implies some deviations from the theoretical cost-effectiveness of the first-best benchmark.

→ As a result, for both efficiency and political economy reasons, we have to think about the specific costs associated with different sectoral measures.

The engineering approach: an example

Figure 1

The McKinsey (2009) Marginal Abatement Cost Curve: "Global GHG Abatement Cost Curve Beyond Business-As-Usual-2030"



Source: Global GHG Abatement Cost Curve v2.0. Figure and notes reproduced with permission from McKinsey (2009).
Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

The McKinsey curve uses engineering estimates to plot the marginal abatement cost of CO_2 abatement measures from the least to the most expensive (excluding those above 60€/tCO_2).

The engineering approach: limitations

From the previous figure, many measures appear to be free lunches: it is possible to reduce emissions and save money at the same time.

If costs can be reduced through these measures, why are not they already induced by market forces?

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If costs can be reduced through these measures, why are not they already induced by market forces?

- The underlying assumption behind these free-lunches is that somehow some polluters (firms, consumers) are not optimizing, such as consumers being myopic and overly discounting future costs.
- A typical example of negative abatement costs arises when there exists an "energy efficiency gap", i.e. when the realized level of energy efficiency differs from the cost-minimizing one (excluding environmental costs).
- However, the existence of such gap remains debated in the literature, as we may suspect it reflects costs that are not properly accounted for in the cost-benefit analysis.

$\rightarrow$ In particular, engineering estimates tend to miss a key element of the cost-benefit analysis: behavioral effects.

The rebound effect in energy consumption

Among the many potential behavioral effects that may follow from a given measure, the rebound effect in energy consumption has been shown to be critical. The basic intuition is the following: if people get a more efficient car (i.e. which consumes less per km traveled) they will drive more.

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As explained by Gillingham et al (2013, 2016), the rebound effect can actually be decomposed into four effects:

- a direct effect: with higher energy efficiency, the unit price of using a utility (ex: driving a car) decreases so its use increases;
- an indirect effect: if money is saved from the efficiency improvement, it may be spent for other energy intensive goods;
- by reducing the demand for energy by a given sector (ex : automobile), it lowers energy prices and may lead to higher consumption in other sectors (or other countries if the improvement is driven by a national policy);
- additional macroeconomic effects, such as technological spill-overs on other industries (ex: technologies used for more efficient cars may lead to more efficient airplanes).

→ According to the authors, all together these effects could reduce the energy savings from an energy efficiency improvement policy by 20% to 60%. Ignoring these effects leads to an underestimation of energy saving costs.

The economic approach (from Gillingham & Stock, 2018)

Table 2

Static Costs of Policies based on a Compilation of Economic Studies

(ordered from lowest to highest cost)

Policy	*Estimate (\$2017/ton CO_{2e})*
Behavioral energy efficiency	–190
Corn starch ethanol (US)	–18 to +310
Renewable Portfolio Standards	0–190
Reforestation	1–10
Wind energy subsidies	2–260
Clean Power Plan	11
Gasoline tax	18–47
Methane flaring regulation	20
Reducing federal coal leasing	33–68
CAFE Standards	48–310
Agricultural emissions policies	50–65
National Clean Energy Standard	51–110
Soil management	57
Livestock management policies	71
Concentrating solar power expansion (China & India)	100
Renewable fuel subsidies	100
Low carbon fuel standard	100–2,900
Solar photovoltaics subsidies	140–2,100
Biodiesel	150–250
Energy efficiency programs (China)	250–300
Cash for Clunkers	270–420
Weatherization assistance program	350
Dedicated battery electric vehicle subsidy	350–640

Note: Figures are rounded to two significant digits. We have converted all estimates to 2017 dollars for comparability. See Appendix Table A-1 for sources and methods. CO_{2e} denotes conversion of tons of non-CO_2 greenhouse gases to their CO_2 equivalent based on their global warming potential.

Take-away from the assessment of static costs

The previous table is based on a review of the relatively recent (after 2006) economic literature by Gillingham & Stock (2018). The main take-away are the following:

1. Between different interventions, the range of costs is very wide;
   - Example: while certain interventions still have negative costs (ex: policies/nudges correcting mis-optimizing behaviors), other policies are much more costly than typical measures of the SCC.
2. Within given kinds of interventions, the range of costs is very wide as well;
   - Example: the costs of subsidies for wind and solar power generation greatly vary depending on the project location, the scale of the program, and its timing (the older ones being more costly).
3. Some of the interventions that had negative costs following the engineering approach have a positive cost in the economic literature;
   - Example: this is typically the case of policies meant to close the energy efficiency gap, because engineering models ignore some costs or do not account for behavioral responses (see Fowlie et al, 2018).
4. There are still some policies with negative costs;
   - Example: policies meant to address mis-optimizing behaviors.

Take-away from the assessment of static costs

5. Some policies have very low costs;
   - Example: the Clean Power Plan in the U.S., that sets target to each US State to reduce power plants emissions, appears to be very cheap according to the US EPA.
6. Some interventions have very high costs;
   - Example: subsidies for solar energy, or standards for vehicle energy efficiency can end up being very costly.
7. We should still be careful with some of these assessments that may not properly identify all relevant marginal costs and benefits;
   - Example: payments for reforestation are known as a cheap way to reduce net emissions. Still, the counterfactual of these policies is often uncertain (does it crowd-out private incentives?) and so are the long-term benefits (if the payments stop, are trees cut again?)
8. Interventions that are the most likely to be extended at a large scale generally appear as more costly;
   - Example: when behavioral nudges are sufficient (ex: for light bulbs) the associated environmental benefits are often limited, while for large scale interventions (ex: ambitious weatherization programs, R&D for electric vehicles, etc.) the costs are often much higher.

Static versus dynamic costs

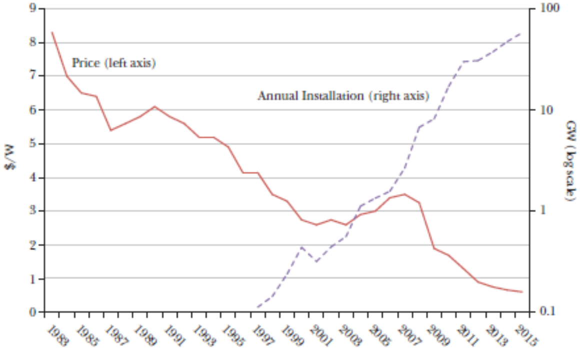
In cost-benefit analysis, accounting for all costs and benefits of a given policy intervention is challenging. For some interventions, long-term spill-over effects are likely to be important.

Gillingham & Stock (2018) list four reasons why dynamic spill-overs may be large for some interventions favouring green technologies:

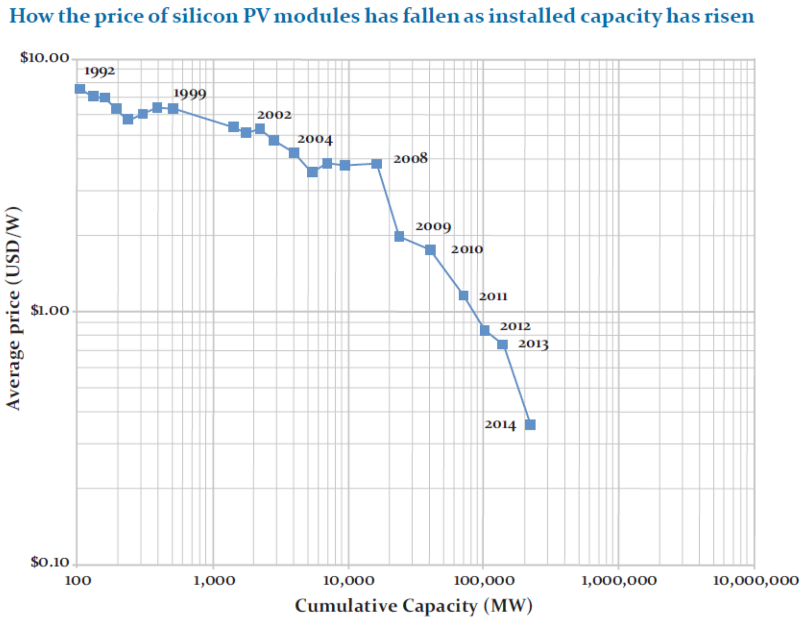
1. learning-by-doing in nascent technologies leading to efficiency gains in production (i.e. economies of scale);
2. positive externalities on research and developments;
3. network externalities;
   - Example: purchasing an electric vehicle increases the demand for charging stations, which benefit other users of electric vehicles.
4. path-dependencies;
   - Example: building a good network of cycling paths has an effect of mobility decisions, residential location choices, etc. Investments in infrastructures may lead people to re-optimize and affect a long chain of decisions.

Figure 2

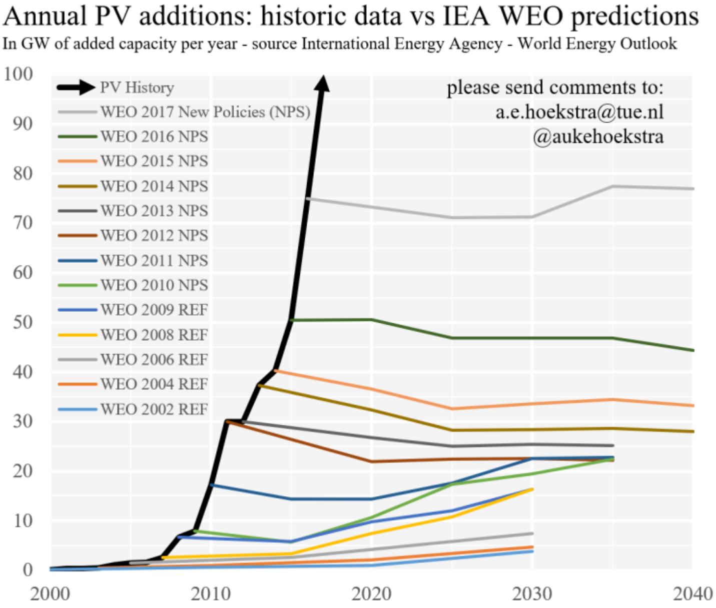
Solar Panel Price Indexes Excluding Subsidies and Cumulative Worldwide Installed Capacity, 1983–2015



Source: International Energy Agency (2017), Navigant Consulting (2009), and Gerarden (2018).



Source: King et al (2015)



Source: graph made and shared on twitter by Auke Hoekstra.

Static versus dynamic costs: the example of solar PV panels

Between 2010 and 2015:

- the price of solar photovoltaic panels fell by two-third;
- the global number of installations increased by 250%.

→ Very rapid change in prices and quantities.

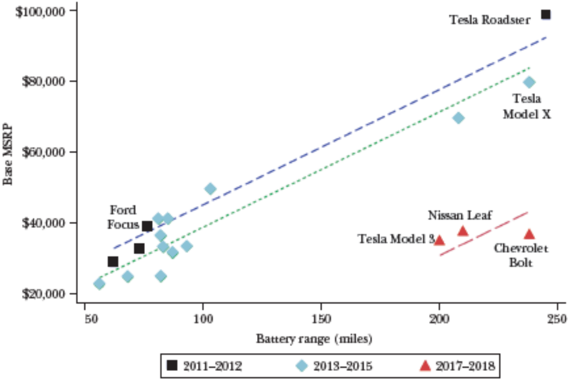
More surprising is the timing of these changes:

- rather continuous decrease in prices since the 80's;
- in the early 2000's, Germany and later California started heavily subsidizing solar PV panels;
- a few years later (around 2007), steepest decline in prices;
- Gillingham & Stock (2018): "In this sense, the German Energiewende subsidized lower-cost solar for the rest of the world";

→ Combinaition of positive spill-over effects and learning by doing: the static costs of solar subsidies likely over-estimate the long term dynamic costs.

Figure 3

Electric Vehicle Manufacturers Suggested Retail Price (MSRP) Plotted against the Battery Range Shows Impressive Technology Improvements within a Short Time



Source: J. Li (2017) and authors' calculations.
Note: Dates indicate year the model is introduced. Regression lines are fit with a common slope and different intercept for each group of model years.

Static versus dynamic costs: the example of electric vehicles

- From a short-term perspective, the costs of subsidies for electric vehicle seem to far outweigh their benefits.
- For example, Holland et al (2016) show that in the US the static optimal subsidy accounting for greenhouse gases and local pollution ranges from 2785$ in California to -4964$ in North Dakota where coal accounts for a large share of the electricity mix.
- In the long-run, the dynamic cost-benefit analysis may however provide different insights:
    - Just as with solar PV panels, positive spill-over effects and learning by doing;
    - Example: from 2009 to 2015, the price of batteries fell by 75%, concommitant to high subsidies on these vehicles;
    - In addition, network effects may be critical: multiple equilibria may exist since an additional user increases incentives to develop public good type of infrastructures that encourage new entrants.

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The climate technology revolution

Barrett (2009): "Emissions of CO_2 and other greenhouse gases can be reduced significantly using existing technologies, but stabilizing concentrations will require a technological revolution—a "revolution" because it will require fundamental change, achieved within a relatively short period of time."

According to Barrett, for such a revolution to occur:

- a price must be put on the climate externality (necessary condition for setting the right incentives);
- financing fundamental R&D is also necessary as this reasearch is not sufficiently rewarded by the patent system;
- multilateral cooperation between governments and with the private sector is needed to ensure the development and dissemination of these technologies.

$\rightarrow$ The focus of the paper is on the potential for new technologies to reduce emissions dramatically.

The figures in the paper are a bit outdated, but the main insights are still valuable.

CO_2-free energy

Energy consumption and the associated release of greenhouse gas emissions being the main driver of climate change, a key challenge is to rapidly transition towards CO_2-free energy globally.

There exists different types of CO_2-free energy, with more or less potential for large scale development, including:

- wind;
- solar;
- nuclear;
- bioenergy;
- hydro-power;
- geothermal;
- ocean energy.

→ Barrett focuses on the first four. Although hydro-power offers interesting opportunities in some regions, in many countries it's potential for further developments is limited.

Still a very long way to go

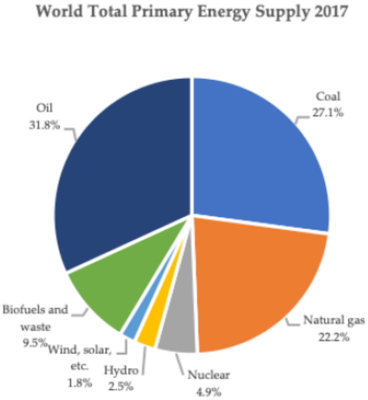
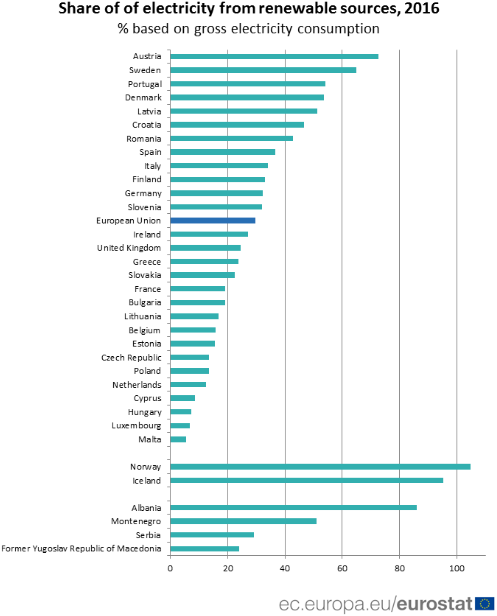


Figure 1. World Total Primary Energy Supply 2017 (Source: IEA).

Share of renewables across countries in Europe



Natural gas dominates the Dutch energy mix

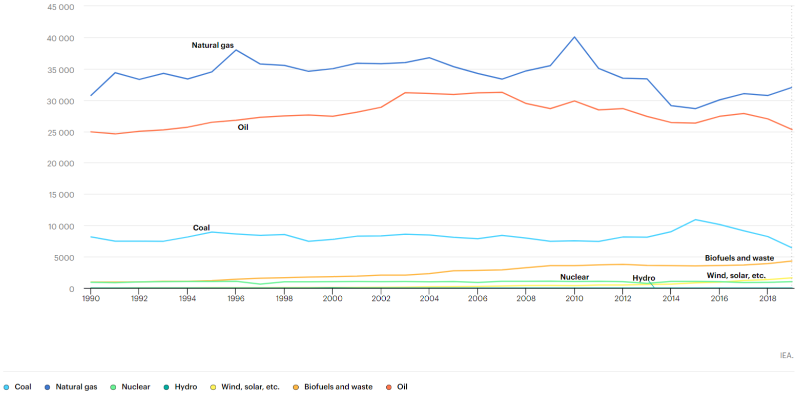


Figure: Total energy supply (TES) by source, Netherlands 1990-2019 (source: IEA)

Wind power

- Wind power production is already economically competitive in many regions of the world.
- Despite continuous improvements, policies will still be necessary to further develop this alternative.
- The larger the price on CO_2, the more it becomes economically attractive to develop wind power projects, and to invest in technological innovation.

Wind power

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- Despite continuous improvements, policies will still be necessary to further develop this alternative.
- The larger the price on CO_2, the more it becomes economically attractive to develop wind power projects, and to invest in technological innovation.
- One important issue however is the intermittency of production. There are several options to mitigate this issue, although none is perfect:
  - demand-side management, i.e. making people consume when electricity-generation is high, for instance through time-dependent electricity-prices $\rightarrow$ problem: acceptability, negative impact on consumers, technically challenging, ...
  - improvement in the grid to reduce the dependency on local weather $\rightarrow$ problem: increases transmission costs, political constraints and lobbying when connecting different countries;
  - storage $\rightarrow$ problem: significantly increases the economic cost from wind power generation.
- Another important limitation: project development depends on the will of local actors, raising a free-rider problem: people are often supportive of renewable energies, as long as they are not the ones hosting the infrastructures (NIMBY). Also holds for off-shore farms.

Solar power

- The economic costs are very heterogeneous depending on the location of the PV farm. In many places in the world it has become cheap enough to compete with fossil fuels, and further decreases in prices have to be expected.
- Still, the challenges associated with solar energy generation are similar to those of wind power.
- Solar is subject to both intermittency and variability (i.e. deterministic variations in production depending on the time of the day and season).
- Absent large scale storage, a large development of solar energy must go together with a back-up – potentially highly polluting – energy.
- Just like wind, solar also requires the use of rare materials (see Hertwich et al, 2014):
  - electricity generation from solar PV panels requires 11 to 40 times more copper than conventional fossil generation;
  - electricity generation from wind power plants requires 6 to 14 times more iron.
- One may also be concerned with the evolution of the EROI (Energy Return on Energy Invested), which represents the ratio between the energy a technology (or the whole energy mix) delivers throughout its lifetime and the energy required to build, operate and dismantle it (cf. Fabre, 2019).

Static EROI for different technologies

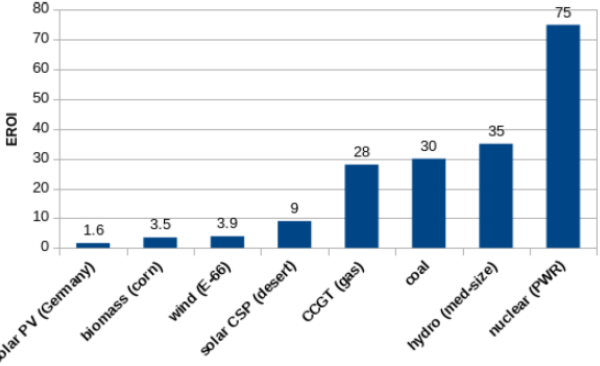


Figure 1: Estimates of EROIs of different electricity technologies, from Weißbach et al. (2013), where supplementary capacity and storage required for the deployment of these technologies is accounted for.

Source: Fabre (2019)

Evolution of the EROI – illustrative example

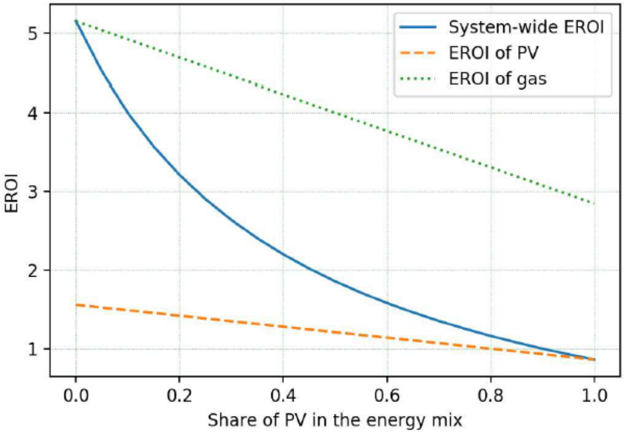


Figure 3: EROIs in the two-technology model in function of the share p of PV in the energy mix.

Theoretical evolution of EROI if substitution towards solar PV, taking arbitrary numbers. Source: Fabre (2019)

Evolution of EROI depending on energy mix

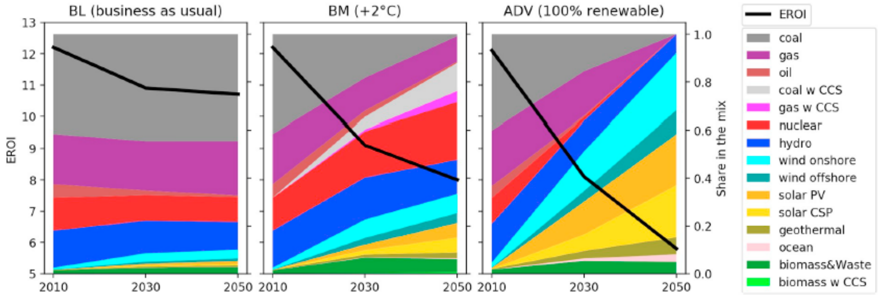
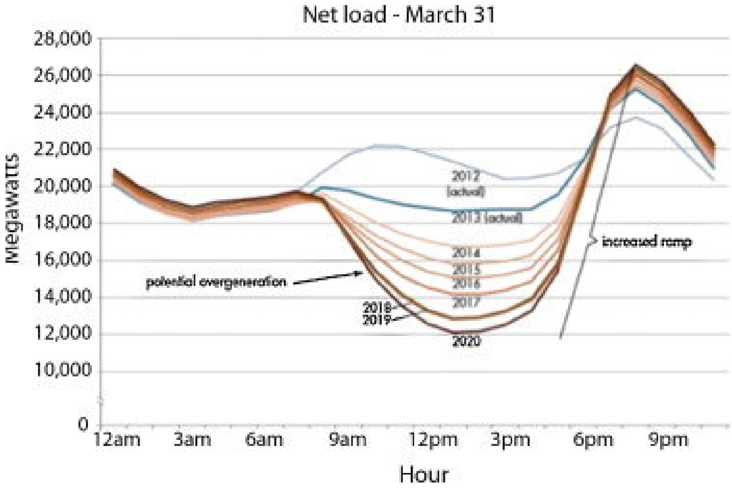


Fig. 4. Evolution of global EROIs and mixes of electricity for different scenarios.

Source: Fabre (2019)

→ Just like for the case of raw materials, there are good reasons to believe that a transition towards a fully renewable global energy production would be possible despite the negative impact on the EROI. Still, some additional costs have to be expected.

The duck chart



Source: California Independent System Operator (CAISO)

Nulcear power

Technically, nuclear power has already the potential to provide carbon-free energy at a very large scale, without the problem of intermittency.

Still, some caveats are in order:

- because of very high initial capital costs, only large scale projects are economically competitive: interesting only for regions with large grid capacity;
- uranium is non-renewable (although scarcity should not be a problem except for the very long-run);
- the price of nuclear has been going up, not down. This is partly due to increasing safety rules, in particular after the Fukushima accident;
- despite these rules, safety will always remain a very critical issue;
- along with the risk of accidents, nuclear-weapon proliferation is also a risk;
- so far, no proper solution has been found for the treatment of nuclear wastes.

$\rightarrow$ Great hope that nuclear fusion will eventually provide abundant CO_2 free energy, but highly unlikely to happen before 2050 (i.e. too late to meet the 2° target).

Bioenergy

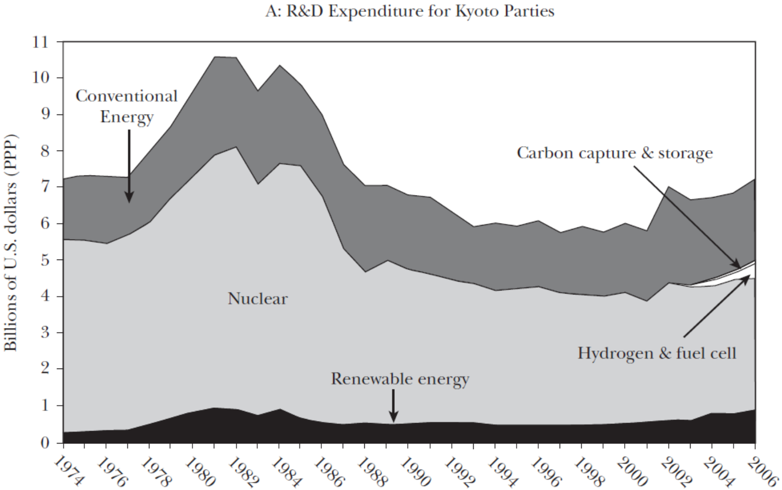
- Biomass energy (or bioenergy) corresponds to energy that is produced from the conversion of biomass, either directly from land products (e.g. wood) or from residues (e.g. crop residues, municipal wastes).
- Bioenergy accounts for most (around 75%) of the worlds' renewable energy consumption.
- Compared to CO_2 free technologies for electricity production, biofuels do not face storage issues, making them atractive in particular for transportation.
- Bioenergy production has also potential co-benefits, such as on agricultural employment in poor countries.
- Still, negative impact on eco-systems, risk of driving deforestation, threat to food security in developing countries, and CO_2 emissions associated with the production of biomass raise important concerns.

$\rightarrow$ Overall, the full chain of consequences greatly depends on which specific biofuels are used. Given the great potential, critical challenge to develop economically competitive large scale production of biofuels with limited negative side-effects.

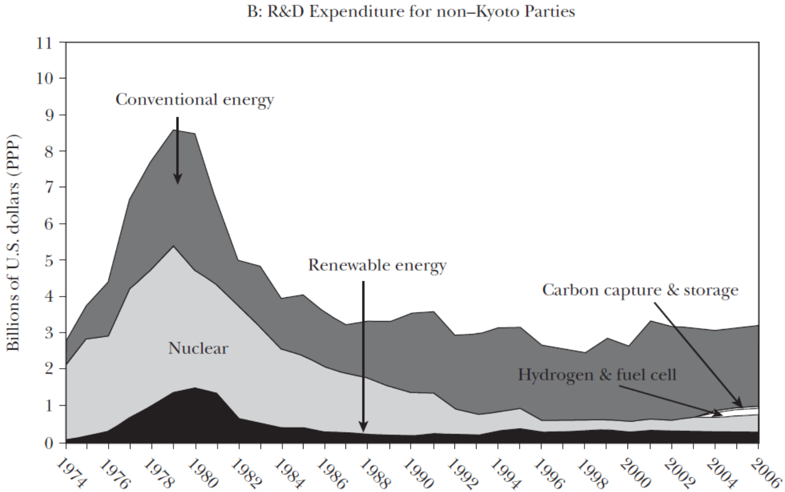
CO_2 capture and sequestration

- Absent a solution to transition away from fossil fuels at the global scale, greenhouse gas emissions will remain too large relative to what the planet can naturally absorb.
- An alternative strategy is therefore to perform "negative emissions", or capture greenhouse gases before they reach the air.
- This strategy is called carbon capture and sequestration (CCS), and may be performed in different ways, including:
  - power plant capture and storage $\rightarrow$ problem: economic cost especially for small facilities, risk of sudden releases of stored GHG.
  - biomass CCS: relatively cheap but $\rightarrow$ problem: difficult to scale it up significantly, sinks would be vulnerable to political changes, and competing uses of land implies negative side effects;
  - ocean fertilization or increased alkalinity $\rightarrow$ problem: the scale is expected to be limited, with possibly significant side effects on ecosystems;
  - industrial air capture: directly absorbing carbon from the air. Can be performed anywhere in the world by any actor $\rightarrow$ problem: for now, very high economic cost, and some governance issues.

$\rightarrow$ Some of these measures are already worth implementing, but overall their costs generally exceed those of emission abatements. Still, the dynamic costs may be lower than the static ones, hence the importance to invest in the most promising projects.



Source: Barrett (2009)



Source: Barrett (2009)

Adaptation and geoengineering

As stressed by Barrett (2009), there will be a climate-technology revolution one way or another. The question is, when and how?

- As climate damages become larger, greater incentives for countries to undertake adaptation measures.
- These adaptations may take many forms: building dikes, relocating populations, increasing trade networks, etc.
- In a scenario where certain countries experience large negative impacts from climate change, these incentives may lead them to a much more radical solution: engineering the climate.

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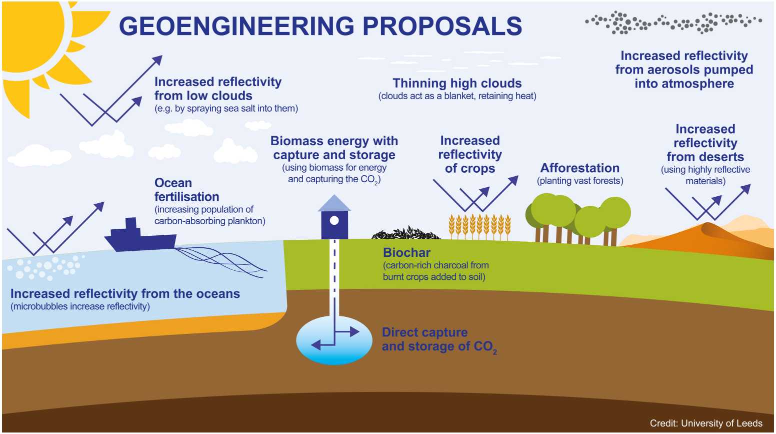
Geoengineering refers to deliberate attempts to modify the climate without lowering greenhouse gases concentrations. These attempts can be made through several methods including increasing the reflectivity of the Earth by painting roofs in white, or injecting aerosols into the stratosphere.

The recent history offers a good natural experiment of this latter alternative: in 1991, the eruption of the volcano Mont Pinatubo would have cooled the earth by 0.5°C for a year (see Crutzen 2006).


GEOENGINEERING PROPOSALS
Increased reflectivity from low clouds
(e.g. by spraying sea salt into them)
Thinning high clouds
(clouds act as a blanket, retaining heat)
Increased reflectivity from aerosols pumped into atmosphere
Biomass energy with capture and storage
(using biomass for energy and capturing the CO_2)
Increased reflectivity of crops
Afforestation
(planting vast forests)
Increased reflectivity from deserts
(using highly reflective materials)
Ocean fertilisation
(increasing population of carbon-absorbing plankton)
Biochar
(carbon-rich charcoal from burnt crops added to soil)
Increased reflectivity from the oceans
(microbubbles increase reflectivity)
Direct capture and storage of CO_2
Credit: University of Leeds

Geoengineering as a public "gob"

- In "The Incredible Economics of Geoengineering" (2008), Barrett reviews evidence suggesting that large scale geoengineering would be extraorinarily cheap, so cheap that any State under the pressure of climate change could undertake it unilaterally.
- Problem: geoengineering is an imperfect subsitute to mitigation (see next slide): although the global average temperature can be chosen, its distribution cannot, and important side effects are expected to arise.

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- In "The Incredible Economics of Geoengineering" (2008), Barrett reviews evidence suggesting that large scale geoengineering would be extraorinarily cheap, so cheap that any State under the pressure of climate change could undertake it unilaterally.
- Problem: geoengineering is an imperfect subsitute to mitigation (see next slide): although the global average temperature can be chosen, its distribution cannot, and important side effects are expected to arise.
- Weitzman (2015) considers geoengineering as a public "gob", i.e. a good that may at the same time be a pure public good for some people, and a pure public bad for others;
- If geoengineering offers an effective way to cool the earth, 1) countries may have heterogeneous preferred temperature, and 2) differently value the side effects of geoengineering / global warming.
- As such, and because of its low price, geoengineering can be see as a free-driver externality, since any individual actor may contribute to the global public gob at virtually no cost.

$\rightarrow$ This free-driver externality creates an additional concern on top of the traditional free-rider externality of climate change. If anyone can play with the global thermostat at no cost, potential conflicts may arise.

Many reasons why geoengineering is a bad idea (from Robock, 2008)

Stratospheric Geoengineering

Benefits

1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, land-based ice sheet melting, and sea level rise
2. Increase plant productivity
3. Increase terrestrial CO_2 sink
4. Beautiful red and yellow sunsets
5. Unexpected benefits

Each of these needs to be quantified so that society can make informed decisions.

Robock, Alan, 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, No. 2, 14-18, 59, doi:10.2968/064002006.

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

Robock, Alan, 2014: Stratospheric aerosol geoengineering. *Issues Env. Sci. Tech.* (Special issue "Geoengineering of the Climate System"), **38**, 162-185.

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Will not stop ice sheets from melting
6. Impacts on tropospheric chemistry
7. Whiter skies
8. Less solar electricity generation
9. Degrade passive solar heating
10. Rapid warming if stopped
11. Cannot stop effects quickly
12. Human error
13. Unexpected consequences
14. Commercial control
15. Military use of technology
16. Societal disruption, conflict between countries
17. Conflicts with current treaties
18. Whose hand on the thermostat?
19. Effects on airplanes flying in stratosphere
20. Effects on electrical properties of atmosphere
21. Environmental impact of implementation
22. Degrade terrestrial optical astronomy
23. Affect stargazing
24. Affect satellite remote sensing
25. More sunburn
26. Moral hazard – the prospect of it working would reduce drive for mitigation
27. Moral authority – do we have the right to do this?

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Main takeaways

What do you think?